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PRESSURE AND MAGNETIC FIELD EFFECTS ON TRANSPORT IN $NbSe_3$

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ABSTRACT

We have performed dc resistance measurements on the charge density wave (CDW) conductor $NbSe_3$, at pressures up to 38kbar, and magnetic fields up to 8T. We show that a magnetic field generates no anomalous magnetoresistance in the lower CDW state if the CDW transition is suppressed by pressure. We also show that the upper CDW state is unaffected by the application of a magnetic field. Furthermore, we show evidence of a possible H-induced phase transition at ~30K.

INTRODUCTION

Recent studies have shown an anomalous magnetoresistance effect in the lower CDW state (T<59K) of the quasi 1-D conductor $NbSe_3$ [1]. The application of a large (20T) magnetic field perpendicular to the chain axes doubles the low field resistance at temperatures where conventional magnetoresistance mechanisms are inapplicable. A model by Balseiro and Falicov (BF) based on the quasi 1-D nature of $NbSe_3$ attempts to explain this anomalous magnetoresistance by suggesting that the H-field increases the 1-D character by destroying conduction electron pockets and thus decreasing the normal carrier concentration [2]. Whilst various transport measurements provide indirect evidence for this mechanism, direct measurements have so far proved contradictory [3-7]. Furthermore, other quasi 1-D conductors with similar electronic structures show no anomalous magnetoresistance [8], so the precise nature of the mechanism responsible for the effect in $NbSe_3$, and whether it is related to the CDW is still unclear.

In this paper we report on the use of pressure (up to 38kbar) and H-fields (up to 8T) to show that indeed the anomalous magnetoresistance is related to the lower CDW state, and is not due to magneto-transport properties of the remaining normal electrons, nor is it related to the upper CDW state which shows no evidence of any magnetoresistance effects. Finally we show some preliminary data which suggests a possible H-field induced phase transition at ~ 30K, which may help to explain the contradictory nature of earlier results.

EXPERIMENTAL DETAILS

Four probe resistivity measurements,were performed on high quality $NbSe_3$ samples, with $R(300K)/R(4K)$ values in excess of 200. The lower pressure experiments (up to 8.5kbar) were performed in a quasi hydrostatic clamp cell, which was known to have a constant pressure below 100K and only a small temperature dependence above this. The higher pressure experiments (32-38kbar) were performed in a diamond anvil cell.

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RESULTS

Figure 1 shows the effect of pressure and magnetic field around the lower CDW anomaly. The well known suppression of both the transition temperature and the size of the anomaly by the application of pressure are clearly seen. At p=1bar, the size of the resistance anomaly indicates that 65% of the normal electrons are removed at the transition, whilst at 4.3kbar, this is reduced to 30%. Application of an 8T field at p=1bar increases the 65% normal electron loss to 71%, whilst at 4.3kbar the loss is increased from 30% to 61%. Above 6.5kbar, the lower CDW transition is completely suppressed. Application of an 8T field will not restore any resistance anomaly. For pressures below 6.5kbar, where the lower CDW state was still present, an 8T field led to a 5x enhancement of the resistance at 4K. For higher pressures, where the transition was suppressed, the H-field only caused a 30% resistance increase at 4K. In agreement with other workers, it was found that to within the experimental accuracy (0.1K), the phase transition temperature was unaffected by the application of the H-field.

Figure 2 shows the effect of pressure and magnetic field on the upper CDW transition. At the lower pressures, the upper CDW state shows no sign of any anomalous magnetoresistance as found for the lower state. At fields up to 8T, the resistance maximum was found to increase by no more than 0.1%. At pressures high enough to suppress the upper CDW state no unusual magnetoresistance effects are seen, only a small increase with field persisting up to about 50K, which we attribute to traditional magnetotransport mechanisms. Interestingly, at the two highest pressures measured (32kbar and 38kbar), the sample underwent a superconducting transition at 5K. This was suppressed by the application of the 8T field.

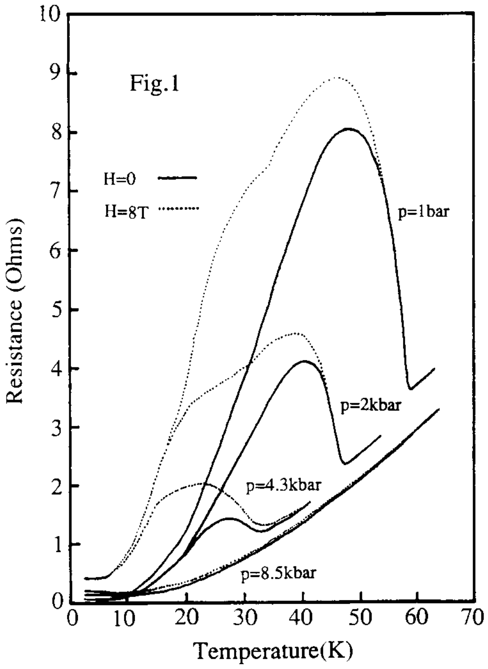

Fig.1 Resistance v Temperature curves for the lower CDW state with H=0 and 8T, for several pressures.

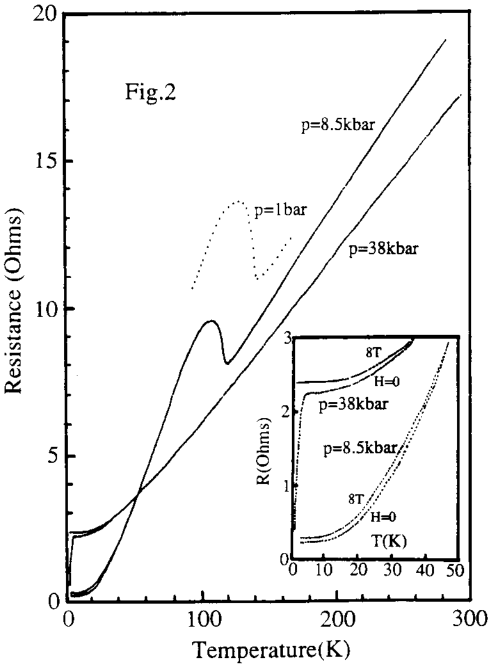

Fig.2 Resistance v Temperature curves for the upper CDW state with H=0 and 8T, for several pressures. The inset shows low temperature detail.

Detailed examination of the lower resistance anomaly

Figure 3 shows in detail the magnetoresistance below 59K. As noted before, the size of the resistance anomaly increases with magnetic field. However, closer inspection shows that the shape of the anomaly has some structure, with a secondary "lump" appearing around 25-30K as the field is increased. This lump is seen particularly clearly in the inset to fig.3, which shows $\Delta R = R(H)-R(0)$, and shows how the size of this secondary lump increases with field and how it shifts to higher temperatures. This lump was completely reproducible, non-hysteretic, and seen for all samples, even when pressure was applied. Also, the size of this secondary lump was independent of the electric field, as long as the field was less than the threshold for CDW depinning. For electric fields higher than threshold, both the major and secondary resistance anomalies were suppressed. An indication of the high quality of the samples was their low threshold fields, with a minimum value of 8.3mV/cm. at 50K.

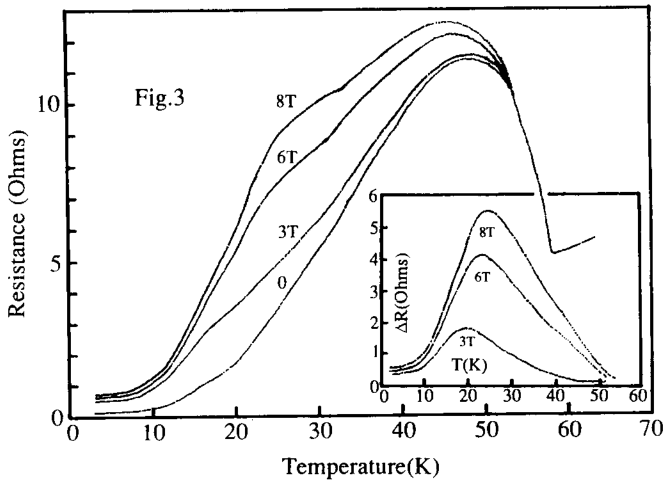

Fig.3 The field dependence of the resistance for the lower CDW state. The inset shows $\Delta R=R(H)-R(0)$ at various fields.

DISCUSSION

The reduction of T_c under pressure for the lower CDW state is seen with or without the H-field. Indeed the transition temperature remains constant when the field is increased for all pressures (<6.5kbar). This combined with the fact that the resistance anomaly cannot be restored by the H-field once pressure has suppressed the CDW transition indicates that the anomalous magnetoresistance must be intimately related to the lower CDW state. It is not related to the normal state electrons, nor the upper CDW. This supports the BF model mentioned earlier. The greater influence of the H-field at higher pressures (up to 6.5kbar) can be understood in this model as the destruction of larger (or extra) normal carrier pockets induced below the Peierls transition as the interchain coupling increases and the sample becomes more 3-D.

The difference in the response to an H-field of the upper and lower CDW is harder to explain. It is possible that the upper CDW state is much more 2-D than the lower, and this would reduce the effectiveness of the BF model to convert carriers. This finds some support from other CDW systems which show no anomalous magnetoresistance, probably as a result of their 2-D nature [8]. However, from energy considerations, it might be expected that the upper CDW is actually more 1-D than the lower, since in order undergo the Peierls transition at the higher temperature it must have a higher generalised susceptibility, i.e. a greater potential for Fermi surface nesting caused by a more 1-D nature. One other possibility is the coexistence of the CDW with both a SDW and a net magnetisation for the lower but not the upper CDW state. Such models have been considered by several authors [9-12] and their models all suggest mechanisms by which the H-field can couple to the density wave and thus modify the Fermi surface.

At higher pressures, where the lower CDW is suppressed, the 4K magnetoresistance is ~ 30%. This is fairly typical for normal metals. However, at p=1bar, where the CDW state is still present, the 4K magnetoresistance is ~400%. This is much larger than might be expected from the reduction in the number of normal carriers caused by the H-field. The magnitude of the resistance around 40-50K indicates that the H-field only induces a further 6-15% normal carrier reduction. This suggests that a further mechanism for carrier loss may be required. We will return to this point later.

The presence of a secondary lump in the magnetoresistance is somewhat unusual and hard to explain in terms of the BF model. However, one possible explanation is the existence of an H-field induced phase transition near 30K. We have performed several other experiments to investigate this possibility, and preliminary data lend support to the idea. Magnetic susceptibility data taken in a 5T SQUID magnetometer indicates a sudden susceptibility decrease below 28K. Magnetothermopower at 1T similarly indicates a large positive enhancement below 30K. The CDW depinning threshold electric field is strongly reduced under H-fields below 30K (also noted by Monceau and Richard [13]). Furthermore, the Hall effect data taken by Ong and Monceau [14] shows a sudden change at 30K, which they explain in terms of a temperature dependent mobility effect in a two carrier system, but which could be explained more simply in terms of a change in the carrier concentration caused by a phase transition. One further measurement of the Young's modulus under magnetic field showed no anomaly greater than 2x10^{-6} near this temperature.

Taken together these data suggest a phase transition near 30K, which causes a decrease in the number of remaining normal state carriers. Such a transition would probably not be of the Peierls type since we see no evidence of any electron-lattice coupling from the Young's modulus data. This idea would be consistent with the large 4K magnetoresistance mentioned earlier. Further work is in progress and will be reported on at a later date.

ACKNOWLEDGEMENTS

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