NON-OHMIC ELECTRICAL TRANSPORT IN THE SPIN-DENSITY WAVE STATE OF ORGANIC CONDUCTORS

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ABSTRACT

We have searched for electric-field-dependent conductivity in the spin-density wave (SDW) ground state of the organic conductors $(TMTSF)_2X$, $X=NO_3$ and PF_6. We have found that the non-ohmic conductivity appears above a finite threshold field (E_T) whose minimum values measured at 4.2K are 5-40 mV/cm. E_T is temperature independent below $T_c/2$ (where T_c is the transition temperature) and varies close to T_c. The excess conductivity is smaller in samples with a lower resistivity ratio. A sliding SDW mode, deppined under high enough electric fields, might be responsible for the observed electric-field-dependent response. We discuss our results in the framework of recent theories for a sliding SDW mode pinned to nonmagnetic impurities and commensurability potential and show that they agree rather well with a theoretically predicted behaviour. Finally, we compare electric-field-dependent transport in the SDW ground state with that observed in the charge-density wave (CDW) state, where CDW sliding is a well established phenomenon.

INTRODUCTION

Various highly anisotropic conductors, both inorganic and organic, are ideal systems for studying collective transport phenomena /1/. Depending on the material and applied pressure, there is usually a phase transition to a superconducting (SC), a charge-density wave (CDW), or a spin-density wave (SDW) ground state at low temperatures. A translational mode of the CDW ground state couples to an applied electric field and gives collective transport. The essential properties of the CDW current-carrying state are as follows: the dc electrical conductivity increases sharply above a finite threshold field (E_T), the conductivity is frequency dependent and the non-linear current-voltage characteristics are accompanied by narrow and broad band noise.

Theoretically, similar behaviour might be expected for a SDW state, because collective transport does not depend on the nature of the underlying interaction mechanism /2/. The quasi one-dimensional SDW model systems are some members of the $(TMTSF)_2X$ family in which the SDW nature of the ground state with a critical temperature of about 10K has been firmly established by various magnetic measurements /3/, /4/, /5/.

The purpose of this paper is to review and discuss recent experiments performed to look for one of the properties of a possible SDW current-carrying state: namely a dc electrical conductivity which increases above a finite threshold field /6/, /7/. We have investigated two materials: the NO_3 and the PF_6 compounds with SDW transition temperatures of 11 and 11.5K and SDW single-particle gaps of approximately 16 and 28K, respectively. As far as the frequency-dependent conductivity is concerned, the results obtained by G.Grüner et al. /8/, clearly show the existence of a collective mode in the SDW state of the PF_6 compound with a pinning frequency of about 30GHz and with a relaxation time and effective mass similar to those of the metallic state. In addition, K.Nomura et al. /9/ very recently reported the first observation of narrow band noise in the SDW state of Quenched ClO_4 crystals.

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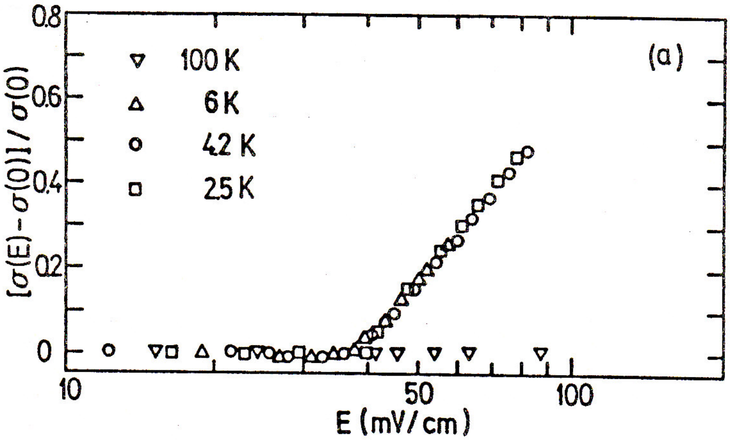
EXPERIMENTAL RESULTS

The electric-field-dependent conductivity observed in the NO_3 and PF_6 compound is shown in Fig.1. In the metallic state the conductivity stays constant in the whole field range measured (up to about 0.7V/cm). However, in the SDW state, the conductivity is constant until a threshold field is reached, above which the conductivity increases. Values of the threshold field measured at 4.2K are 40 and 7.5mV/cm for the NO_3 and PF_6 compound, respectively. The sharpness of the threshold field was checked by continuous current measurements (see insert of Fig.1.b.) and by dynamic resistance measurements (Fig.2.). The excess conductivity is smaller in samples with a lower resistivity ratio $\rho(RT)/\rho(min)$ (Fig.3.). Finally, the excess current associated with the field-dependent conductivity is displayed in Fig.4. In addition, a certain amount of impurities which is large enough to broaden the SDW transition, but does not affect T_c, strongly increases E_T giving a value



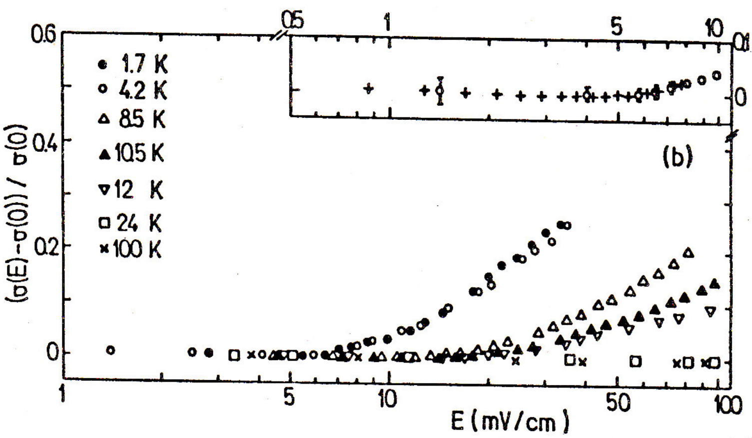


Fig.1. Non-ohmic conductivity $\sigma(E)-\sigma(E\to0)/\sigma(E\to0)$ versus logarithm of electric field (E) at various temperatures for (a) $(TMTSF)_2NO_3$ and (b) $(TMTSF)_2PF_6$.

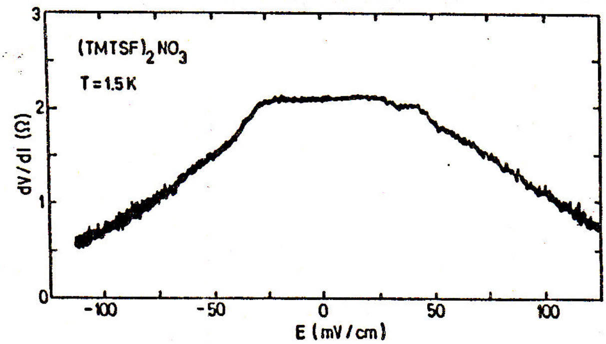


Fig.2. Dynamic resistance (dV/dI) versus electric field (E) for a $(TMTSF)_2NO_3$ crystal at 1.5K.

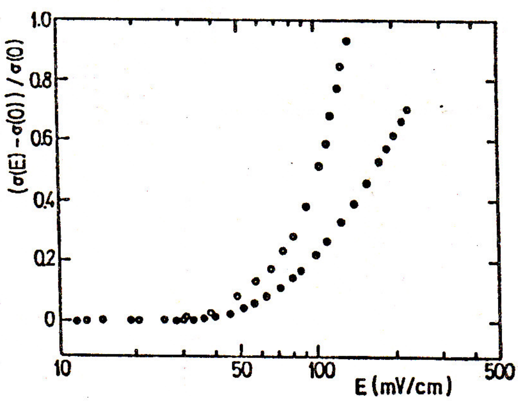


Fig.3. Non-ohmic conductivity for two samples of $(TMTSF)_2NO_3$ at 1.5K with different resistivity ratio (rr). Open and close circles for rr$\simeq$170 and 60, respectively.

as high as $E_T \simeq 140$mV/cm at 1.7K for the PF_6 compound. Furthermore, for both NO_3 and PF_6 the value of the threshold field is temperature independent below $T_c/2$. For the latter we also established the overall temperature dependence of E_T as presented in Fig.5. Its value is constant in temperature until about 5K, but then it changes a further approaching T_c. The changes depend on the type of contacts used, for clamp contacts E_T increases only very close to T_c.

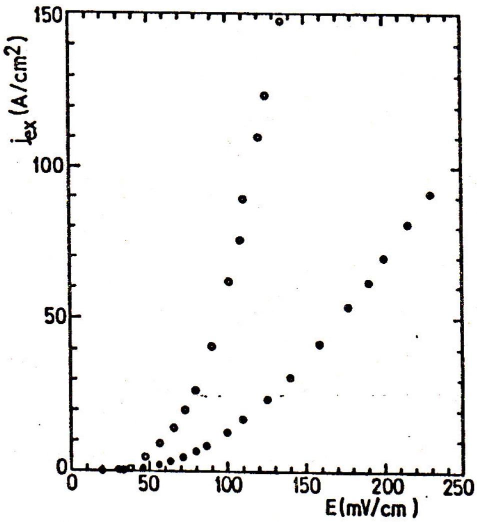


Fig.4. Excess current (j_x) versus electric field (E) for two samples of $(TMTSF)_2NO_3$ with different resistivity ratio (rr). Open and close circles for rr$\simeq$170 and 60, respectively.

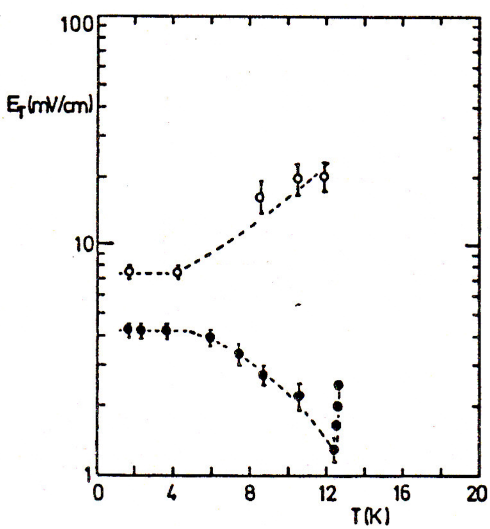


Fig.5. Threshold field (E_T) versus temperature (T) for $(TMTSF)_2PF_6$.Open and close circles for samples with painted and clamp contacts, respectively.

DISCUSSION

The onset of non-ohmic conductivity at the three-dimensional SDW ordering temperature strongly suggests that the nonlinearity is associated with the establishment of a SDW indeed. It is difficult to explain the observed effects using models based on a single-particle picture like Zener breakdown and hot-electron effects /6/. Our results are reminiscent of those in the CDW systems where the nonlinearities have been attributed to the sliding CDW becoming depinned in high enough electric fields.

However, the threshold field does not seem to diverge at T_c, as for most CDW materials and in addition, the increase of E_T at low temperatures, which has been observed for most CDW materials is clearly absent for the SDW. Above $T_c/2$, for samples with painted contacts E_T shows a steady increase towards T_c: $E_T(T_c)/E_T(1.7K) \simeq 2.5$. Such a behaviour has been predicted by Maki and Virosztek /10/ in the framework of the mean-field model for a sliding SDW mode pinned to nonmagnetic impurities. The theoretically expected values for E_T rise are 1.33 and between 1.77 and 3.13 for the strong and weak pinning limits, respectively. In addition, the observed values of threshold fields are close to the ones theoretically expected.However, for samples with strain-free clamp contacts, E_T displays a minimum above $T_c/2$ before increasing very close to T_c. It is worth noting that for these samples the behaviour of the low field resistivity close to T_c is far from that expected in mean-field theory. A similar, extremely sharp SDW transition was also observed by NMR measurements /11/. In that case, the temperature dependence of the threshold field agrees with a pinning mechanism due to commensurability between the SDW and the underlying lattice /12/. Therefore, there exists two limiting situations: in a clean sample the SDW is pinned by a commensurability potential and, on the other hand, for a sample containing more defects (possibly introduced by microcracks) the impurity potential may be the dominant pinning mechanism. The importance of the latter is also indicated by the observation that the excess conduction is smaller in samples with a lower resistivity ratio and that the threshold field is larger in samples with higher impurity concentrations.

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