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

S. Tomic*, J.R. Cooper*, W. Kang and D. Jérôme*

*Institute of Physics of the University, POB 304, 41001 Zagreb, Yugoslavia
+Laboratoire de Physique des Solides, Université de Paris-Sud, 91405 Orsay, France

ABSTRACT
We have searched for electric-field-dependent conductivity in the spin-density wave (SDW) ground state of the organic conductors (TMTSF)$_2$X, 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, doped 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 discuss the agreement with the predictions of these theories. Finally, we compare the 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 behavior 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)$_2$X 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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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 $\rho(\text{RT})/\rho(\min)$ (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

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**Fig. 1.** Non-ohmic conductivity $\sigma(E)-\sigma(E+0)/\sigma(0)$ versus logarithm of electric field ($E$) at various temperatures for (a) (TMTSF)$_2$NO$_3$ and (b) (TMTSF)$_2$PF$_6$. 

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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 $\rho(\text{RT})/\rho(\min)$ (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. 2. Dynamic resistance (dV/dI) versus electric field (E) for a (TMTSF)$_2$NO$_3$ crystal at 1.5K.

Fig. 3. Non-ohmic conductivity for two samples of (TMTSF)$_2$NO$_3$ at 1.5K with different resistivity ratio (rr). Open and close circles for rr=170 and 60, respectively.

as high as $E_T = 400$ 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 \((\text{TMTSF})_2\text{NO}_3\) with different resistivity ratio \( rr \). Open and close circles for \( rr=170 \) and 60, respectively.

Fig. 5. Threshold field \( E_T \) versus temperature \( T \) for \((\text{TMTSF})_2\text{PF}_6\). 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 $T_c$: $E_T(T_c)/E_T(1.7K)\approx2.5$. 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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REFERENCES