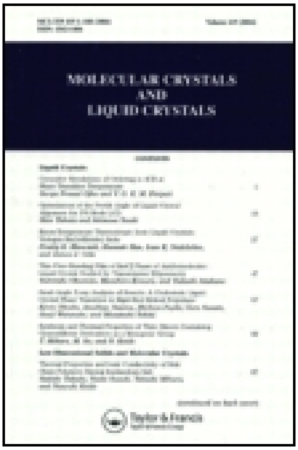

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Dynamical Properties of the CDWs in $NbSe_3$

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DYNAMICAL PROPERTIES OF THE CDWs IN $NbSe_3$

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Above the electric critical field E_c where the CDWs in $NbSe_3$ are depinned, noise is generated in the sample. This noise consists of broad band noise and quasi periodic noise. For many samples we have measured the fundamental frequency ν in the noise as a function of E for the two CDWs. These frequencies can be synchronised by an external rf field as seen by peaks in the dV/dI characteristic. These peaks correspond to an increase in the differential resistance. We show that the current J_{CDW} carried by the CDW is the superposition of a continuous one and a modulation due to the pinning with the fundamental frequency ν that we calculate as a function of the electric field E. When ν is calculated as a function of J_{CDW} we obtain a linear variation where the slope is proportional to the number of electrons affected in the band by the CDW gap. We verify the linear variation between J_{CDW} and ν and we find the same slope for the two CDWs. We deduce that the number of electrons affected by the gap is around $1.0\ 20^{21}\ cm^{-3}$ for each CDW. We obtain a coherent description of the electronic concentration in $NbSe_3$ between the room temperature value given by band calculations, the number of electrons condensed by each CDW and the electronic concentration at low temperature obtained from the measurement of the linear γ term in specific heat.

INTRODUCTION

One of the principal aims of research on one-dimensional compounds during the last decade has been the observation of superconductivity by the motion of charge density waves (CDWs) as predicted by Fröhlich[1] in 1954. For a linear chain, below a critical temperature, a permanent periodic distorsion occurs with the opening of a gap at the Fermi level which is the one-dimensional Peierls metal-insulator transition. However for a system which is totally invariant by translation, the phase of the CDW is arbitrary and Fröhlich has demonstrated that the CDW can move without attenuation with a constant speed and the ground state would be a superconducting state. Practically this translation invariance is broken by several mechanism as impurities, commensurability with the host lattice or Coulomb interactions between chains[2]. The CDW is pinned and the ground state is an insulating state.

Some of linear transition metal trichalcogenides as $NbSe_3$ [3], TaS_3 [4,5] undergo structural transition and in these systems the CDW can be easily depinned with electric fields as low as 0.1 V/cm to 1 V/cm [6,7]. The Fröhlich superconductivity has not been observed but it is shown that the CDW moves and can carry a current.

The temperature variation of the resistivity of $NbSe_3$ show two strong anomalies at T_1 = 145 K and T_2 = 59 K which were ascribed to the CDWs formation. The wave vectors of the distorsions are incommensurate with the lattice and respectively q_1 (0, 0.243±0.003, 0) at T_1 and q_2 (1/2, 0.259±0.003, 1/2) [5,8,9] at T_2. Below T_2 gaps consecutive to the lattice distorsion do not affect the whole Fermi surface and $NbSe_3$ remains metallic at low temperature.

NON-LINEAR CONDUCTIVITY

The amplitudes of the resistive anomalies of $NbSe_3$ are strongly reduced with weak electric fields [6] and are frequency dependent[10,11]. This extra conductivity is associated with the motion of the CDW when the energy gained by the electric field overcomes the pinning energy. This depinning field E_c was calculated by Lee and Rice[12] and observed by Fleming and Grimes[13]. The variation of the conductivity with the electric field was obtained by Bardeen[14] (this conference).

FOURIER ANALYSIS OF THE NOISE ABOVE THE THRESHOLD FIELD E_c

Above the threshold field E_c where non-linearity starts, Fleming and Grimes[13] have shown that noise is generated in the sample between the voltage leads. This noise consists of the superposition of a broad noise and periodic structures. We have made a Fourier analysis of the ac noise voltage with a spectrum analyzer. Fig. 1 shows the Fourier spectrum for different electric fields at T=35.9 K for a sample with E_c = 80.4 mV/cm. Just above E_c a funda-

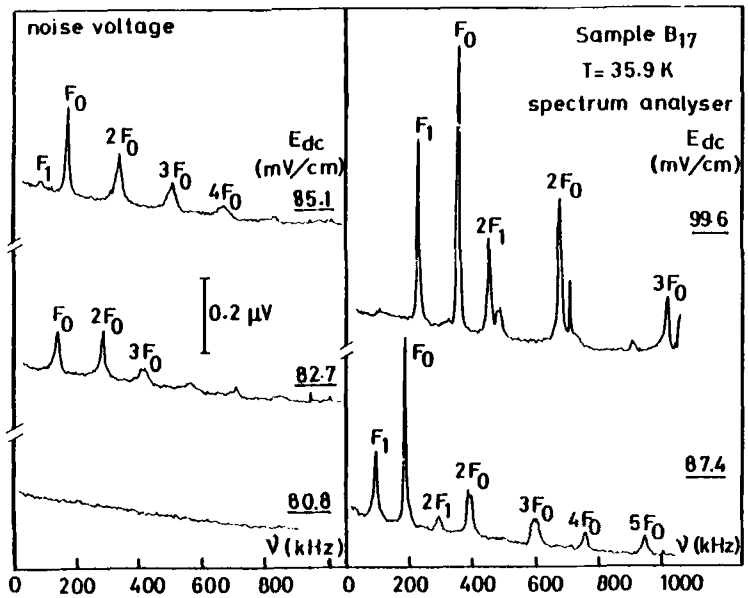

FIGURE 1 Fourier spectrum obtained by direct noise analysis with a spectrum analyzer. The critical field is E_c = 80.4 mV/cm. Fundamental frequency F_o appears first then F_1 and F_2.

mental frequency F_o appears with its harmonics. When E is increased further, a second fundamental F_1 and also a third one F_2 are detected. The whole frequency spectrum can be described with three fundamental frequencies and then harmonics.

We have interpreted these frequencies as the modulation of the current carried by the CDW in the anharmonic potential created by the impurities[15]. The CDW can be thought of as a particle with mass, charge and friction. The current carried by the CDW in motion is :

$$J_{CDW} = - nev_{drift}$$

where v_{drift} is the drift velocity of the wave and ne the number of electrons condensed below each CDW gap. The equation of motion of the CDW (for more details see ref. 16 and the similar model of Grüner and al[17]) contains also pinning forces which we reasonably assume to be periodic with the phase of the CDW at the pinning centers. So the motion due to an external field is the superposition of a continuous drift and a modulation due to pinning at a fundamental frequency

$$\nu = \frac{Q}{2\pi} v_{drift}$$

where Q is the lattice distorsion vector.

Since the pinning is strongly anharmonic we expect many harmonics in the Fourier expansion of the velocity with the fundamental frequency given above. So the current is modulated at ν and its harmonics and gives rise to quasi periodic noise.

SYNCHRONISATION OF THE MOTION OF THE CDW BY AN EXTERNAL rf FIELD

In Fig. 2 we show the effect of the superposition of a rf

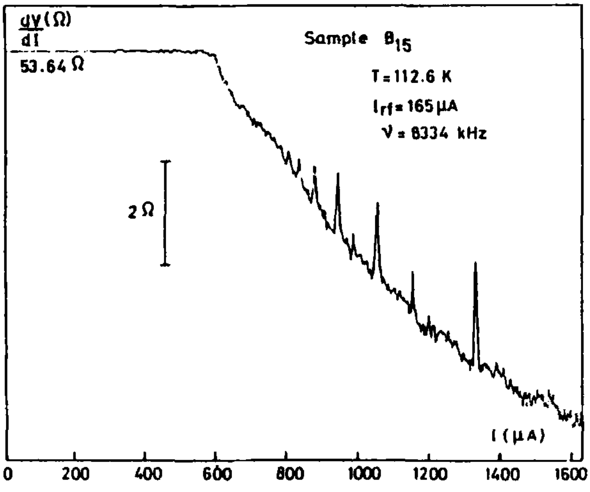

FIGURE 2 Differential resistance dV/dI (at 33 Hz) as a function of the dc current swept in the sample on which a rf field at 8.334 MHz is superposed. Peaks indicate synchronization of the noise frequencies with the external frequency.

current on a dc one in the dV/dI characteristic. We have applied to the sample a rf current with a constant amplitude and a fixed frequency and we have swept the dc current. The differential resistance (at 33 Hz) shows the same features than without rf current (see Richard, Monceau and Renard, this conference). dV/dI is constant up to the critical electric field when non linearity appears. But the effect of the rf field is characterized by the presence of several peaks. In the depinned regime the current carried by the CDW has an ac component which is a function of the electric field in the sample. When the frequency of this modulated current is equal to the external rf frequency there is interference as seen by an increase in dV/dI. In practice we keep constant the dc current (higher than the critical one) and the amplitude of the rf current and we sweep the frequency of this rf current. Typical dV/dI characteristics (at 33 Hz) as a function of the frequency for the two CDWs are shown in Fig. 3.

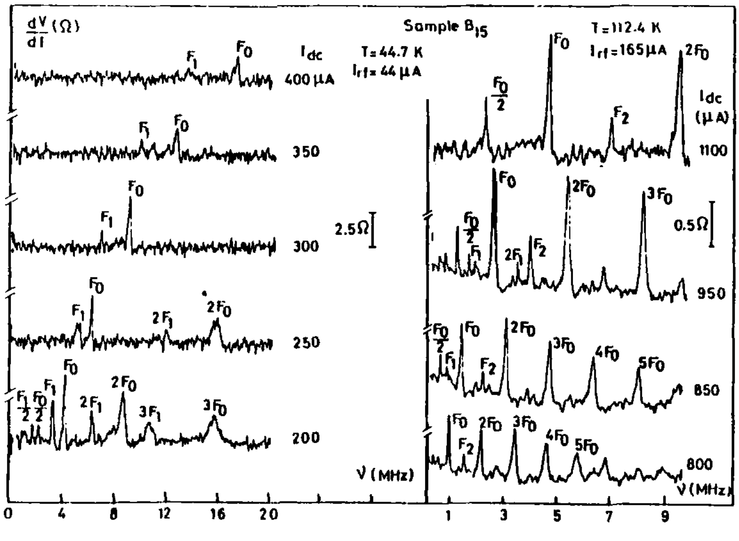

FIGURE 3 Differential resistance dV/dI (at 33 Hz) as a function of the external frequency applied to the sample with a constant amplitude for different dc currents higher than the critical one. At 112.4 K (upper CDW) the critical current is 600 μA and at 44.7 K (lower CDW) the critical current is 73 μA.

The fundamental frequency F_o is defined as the first frequency which appears when the rf amplitude is increased. Many subharmonics are also detected. The fundamental frequencies obtained by direct noise analysis or by the synchronization experiment are the same except near E_c where the coupling between the ac and dc fields changes E_c. In Fig. 4 we have plot the variation of the fundamental frequency for the two CDWs.

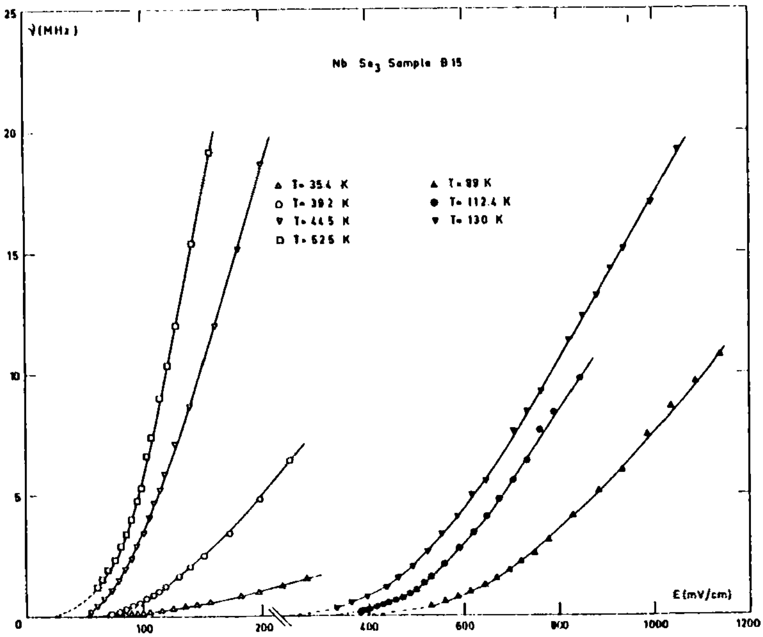

FIGURE 4 Variation with the electric field of the fundamental frequency in the noise measured in the synchronization experiment for different temperatures concerning the two CDWs.

The frequency spectrum can also be analysed with three fundamental frequencies with the two fundamental satellites ν_1 and ν_2 which appear from each side of the fundamental $_o$.

In Fig. 5 we have drawn the variation of ν_o/ν_1 and ν_o/ν_2 as a function of E/E_c. For the two CDWs at relatively low E/E_c ($E/E_c \sim 3$) for the upper CDW and ~ 2 for

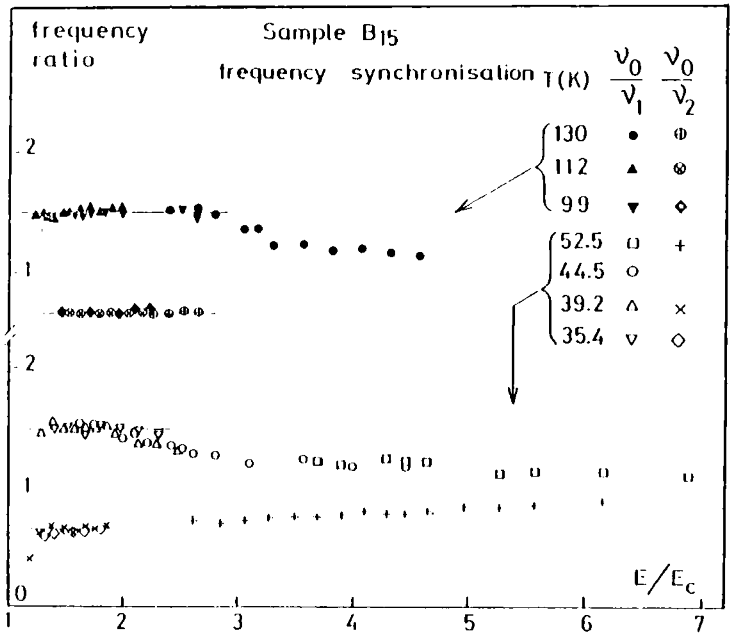

FIGURE 5 Variation with E/E_C of the ratio between the satellite fundamental frequencies ν_1 and ν_2 with the fundamental ν_o obtained in the synchronisation experiment. The upper part is for the upper CDW, the lower part for the lower CDW. At low E/E_C, ν_1 and ν_2 are respectively $(2/3)\nu_o$ and $(3/2)\nu_o$.

the lower one) $\nu_o/\nu_1 = 1.50\pm0.03$ and $\nu_o/\nu_2 = 0.67\pm0.02$. At higher electric field the three fundamental frequencies converge together but however they are distinctable at least up to 100 MHz.

ELECTRONIC CONCENTRATION CONDENSED UNDER THE CDW GAPS

The phenomenological description of the motion of the CDW that we have described above leads to a linear relationship between the fundamental frequency of the modulated current and the amplitude J_{CDW} of the current carried by the CDW.

$$\nu = \frac{Q}{2\pi}\frac{1}{ne} J_{CDW}$$

This current J_{CDW} can be obtained experimentally from the non linear V(I) characteristics if we assume that the conductivity of normal electrons is not affected by the motion of the CDW.

Therefore

$$J_{CDW} = J(1 - \frac{R}{R_n})$$

where J is the applied current density, R the resistance of the sample at J and R_n the resistance of the sample in the ohmic regime. In Fig. 6 we have plotted the same frequencies than in Fig. 4 but as a function of J_{CDW} that we have measured at each temperature.

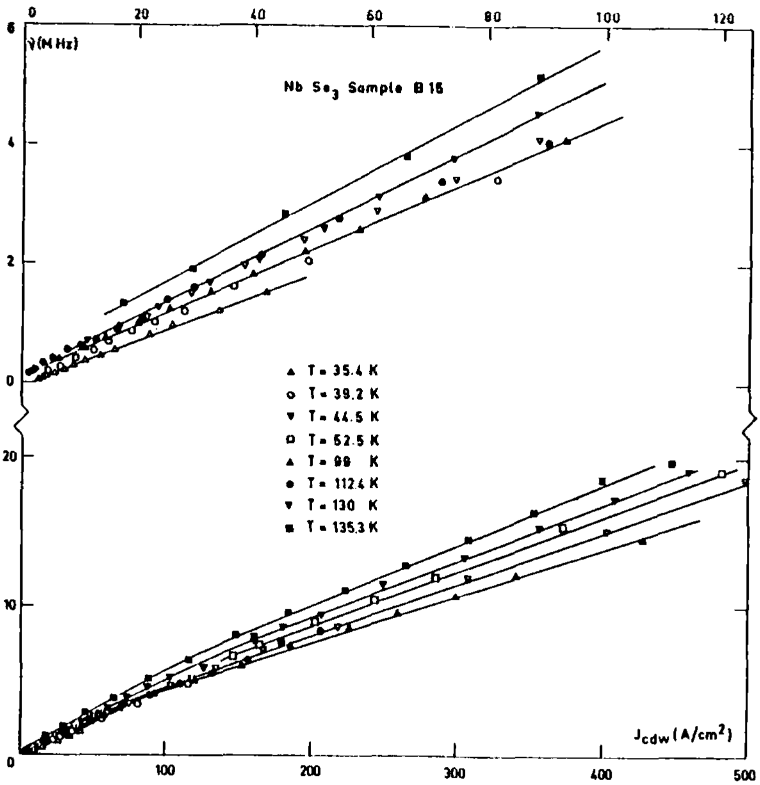

FIGURE 6 Variation of the fundamental frequency ν_0 in the noise as a function of the current J_{CDW} carried by the CDW for the two CDWs. In the upper part for $J_{CDW} < 100$ A/cm^2, in the lower part for J_{CDW} up to 400 A/cm^2.

All the $\nu(E)$ curves gather in a compact pattern. ν is linear with J_{CDW} up to around 100 A/cm^2 and shows a slight curvature for higher J_{CDW}. The cross section of the sample was calculated from its resistance at room temperature and its length assuming a room temperature resistivity of 250 μΩcm.

The slope of ν as a function of J_{CDW} is inversely proportional to ne : the electronic concentration condensed below the CDW gap. Our results show that electronic concentration is the same for each CDW in $NbSe_3$ and around 1.0×10^{21} cm^{-3}. Band calculations[18] show that only four chains (the unit cell is formed by six chains) participate to the conduction. From estimation of the ionicity of the bondings between Se-Se atoms we have concluded that there are two electrons by unit cell to be shared between four niobium atoms[16] and the total number of electrons at room temperature would be 3.9×10^{21} cm^{-3}. From the linear specific heat measured between 0.15 K and 1 K (γ = 24.5 erg/gr.K^2, we have deduced[19] that the number of electrons which remain below the two CDWs is around 10^{21} cm^{-3} which with our measurements of the electronic condensation by the CDW gaps give a coherent picture of the electronic concentration in $NbSe_3$.

CONCLUSIONS

We have studied the noise generated in $NbSe_3$ above the critical electric field where the non-linearity starts. We have performed the synchronization of the quasi periodic noise by an external rf field. We noted that the two CDWs in $NbSe_3$ behave similarly. It appears well established that the non-ohmicity of $NbSe_3$ is due to the motion of the CDWs. A sufficient electric field is necessary to overcome the pinning energy. Above this critical field the current is formed by the superposition of a continuous one and a modulation with a fundamental frequency and harmonics. We have shown that this fundamental frequency is a linear function of the current carried by the CDW and we have deduced the number of condensed electrons under each CDW gap which is in agreement with band calculations.

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