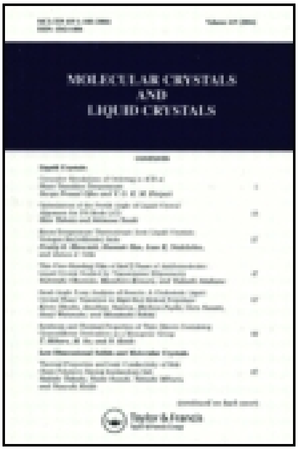

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Study of the Differential Resistance dV/dI as a Function of the Electric Field in the CDW State of $NbSe_3$

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STUDY OF THE DIFFERENTIAL RESISTANCE dV/dI AS A FUNCTION OF THE ELECTRIC FIELD IN THE CDW STATE OF $NbSe_3$

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We have measured the variation of the differential resistance as a function of the electric field for temperatures below those at which the two CDWs form in $NbSe_3$. dV/dI decreases above a critical electric field E_c. We have studied the variation of E_c with the amount of impurities as tantalum, zirconium, titanium. The shape of dV/dI is very sensitive to the temperature especially below that where the resistive anomaly due to the lower CDW shows its maximum. We have observed for same samples a very sharp drop with a deep minimum in dV/dI at E_c. Over a large range of electric field below this dip we have measured low frequency noise without decrease in dV/dI. We also have studied the depinning of the CDW by a ac field with large amplitude.

INTRODUCTION

$NbSe_3$ undergoes two charge density waves transitions (CDWs) at T_1 = 145 K and T_2 = 59 K. The wave vectors of the distorsions associated to the CDWs are incommensurate with the host lattice. The resistivity anomalies which are the consequence of the formation of gaps at the Fermi level are strongly reduced by weak electric fields[1] and are frequency dependent.[2,3] It was shown by Fleming and Grimes[4] that the non-linearity starts only above a critical electric field E_c. Above E_c noise is generated in the sample. The Fourier analysis of this noise reveals periodic structures. We have interpreted these frequencies as the modulation of the current carried by the CDW in motion is the anharmonic potential created by the impurities[5] (see also Monceau, Richard, Renard, this conference). Hereafter we report measurements of the variation of the differential resistance dV/dI as a function of the electric field at different temperatures. With these measurements we can study the onset of the non-linearity in $NbSe_3$ namely, the temperature variation of the dV/dI characteristics, the effect of impurities on the depinning electric field, the frequency dependence of this critical field and finally the effect of an ac electric field on the dc characteristic.

TEMPERATURE DEPENDENCE OF dV/dI

Fig. 1 shows a typical variation of dV/dI (at 33 Hz) as a function of the applied current at different tempera-

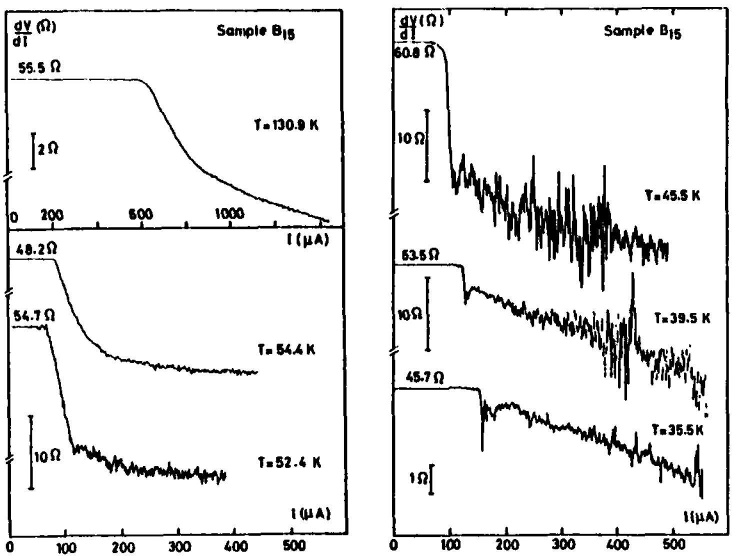

FIGURE 1 Variation of the differential resistance dV/dI as a function of the applied current at different temperatures for the two CDWs in $NbSe_3$.

tures for many $NbSe_3$ samples that we have measured. As found previously by Fleming and Grimes[4] the differential resistance is constant up to a critical current (or critical electric field because in all our measurements we regulate the current, so $I_c = (\ell/R)E_c$) above which it decreases and noise (here at 33 Hz) is generated in the sample. For the upper CDW transition or near T_2, dV/dI follows a similar behaviour than reported by Fleming. But when T decreases, below typically 52 K, dV/dI shows a very sharp drop with a minimum in an electric range of a few percent of the critical field. For higher fields dV/dI decreases slowly with the current. This behaviour is not related to the purity of the sample. Samples doped with titanium or tantalum do not have such a drop at E_c. At lower temperature (around 40 K) before the decrease of dV/dI there is an electric field range where noise is observed without variation of dV/dI. This electric range is more and more large when T decreases. This regime will be studied below.

We have developped a phenomenological model[6] in which we stipulate the existence of domains in which the phase of the CDW is constant. We have supposed that the order parameter is zero in the borders between two domains. In each domain we have described the motion of the CDW assuming that the pinning forces have the same periodicity than the CDW. At E_c we find that for a monodomain, the differential resistance has a negative infinite value in the regime where the current is regulated. This divergence can be suppressed if we consider the sample as formed of many domains and if we assume a distribution of depinning fields for the domains. To explain the variation of the shape of dV/dI in a few degrees below T_2, we must conclude that the width of the distribution of critical fields varies with temperature but in a temperature range where the coherence length of the CDW does not change anymore.

IMPURITY EFFECT ON THE CRITICAL ELECTRIC FIELD

The pinning of the CDW by impurities has been well studied by Lee and Rice[7] which have calculated the strength of the electric field to depin the CDW. They distinguish two kinds of impurity centers : strong pinning where the phase of the CDW is fixed at the impurity: E_c varies as the impurity concentration and weak pinning when the phase of the CDW is fixed in a domain where the size is inversely proportional to the impurity concentration. In this case Lee and Rice have calculated that E_c varies as c^2. Doping $NbSe_3$ with tantalum which is iso-electronic with niobium, Brill and al[8] have found a c^2 dependence of E_c. After irradiation with protons, Fuller and al[9] show that E_c varies as c. In Fig. 2 we show the variation of E_c (measured at the temperature where the resistivity anomaly for the lower CDW is maximum) as a

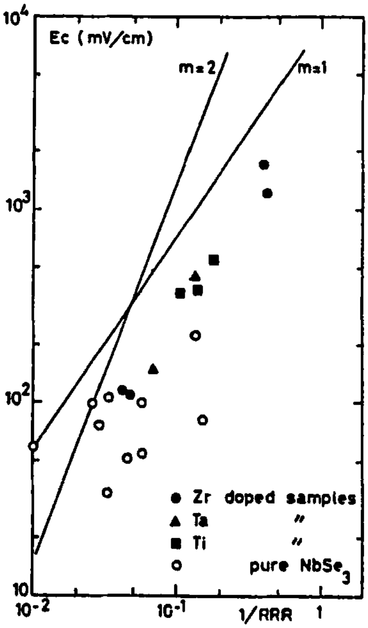

FIGURE 2 Variation of the critical electric field (at the temperature where the resistivity is maximum for the lower CDW) as a function of the inverse of the resistance ratio for $NbSe_3$ doped samples.

function of the inverse of the resistance ratio for samples doped with niobium, zirconium and tantalum. All these impurities seem to have the same effect and E_c follows a linear variation with the amount of impurities. Finally after irradiation with electrons we have found [10] that E_c is very weakly dependent on the number of defects -in fact the depinning occurs at the same critical current independently of the dose of irradiation.

FREQUENCY DEPENDENCE OF THE DEPINNING ELECTRIC FIELD

As we said before a general feature of the variation of dV/dI at low temperature is the onset of noise at a first critical field without decrease of dV/dI in a large electric field range before the sharp drop in dV/dI at a second critical field. This behaviour is illustrated in the top of Fig. 3. We have analysed the frequency depen-

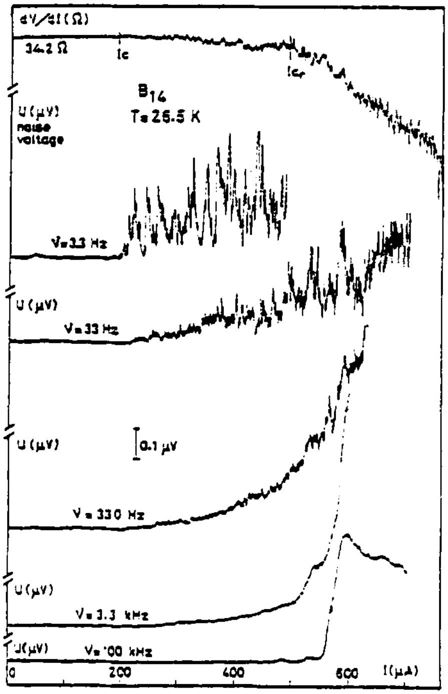

FIGURE 3 Voltage noise as a function of the applied current at different frequencies for a $NbSe_3$ sample at low temperature. Two critical electric field can be defined. In the top of figure, variation of dV/dI.

dence of this noise with a PAR lockin used in the ac mode. The voltage noise increases at the first critical field at 3.3 Hz whereas at 100 kHz it increases only when dV/dI drops strongly (Fig. 3). We demonstrate like this that the definition of the critical field by the onset of the noise is ambiguous because depending on the frequency. We associate the low frequency noise as the depinning of individual domains and the sharp drop in dV/dI as the synchronisation between all the depinned domains. The two critical electric fields that we detect converge into a unique field at the temperature when the resistivity is maximum for the lower CDW around 47 K.

DEPINNING OF THE CDWs BY AN ac FIELD

We sweep in the sample the amplitude of an ac field at a given frequency and we measure the dc characteristic. For more precision we measure the differential resistance at 33 Hz. Fig. 4 shows the variation of dV/dI as a function of the rms amplitude of the ac field for different frequencies. dV/dI shows a sharp threshold. Above this critical field, around 100 kHz, peaks are observed in the dV/dI variation. This behaviour is similar to what we have observed in the variation of dV/dI as a function of a dc current and the superposition of an ac field (see Fig. 2, Monceau and al, this conference). In the present case there is no dc current but when the drift velocity of the CDW is equal to the applied frequency there is interference between the two frequencies. The insert of Fig. 4 shows the variation of the ac (rms value) threshold field as a function of the frequency. Around 100 kHz this ac field is equal to the dc threshold field when a dc current is swept in the sample. Above 100 kHz I_c^{ac} decreases and varies linearly with Log ν up to 2 MHz.

CONCLUSIONS

The depinning of the CDWs in $NbSe_3$ is very well demonstrated in the differential resistance measurements. The temperature variation of the shape of dV/dI gives information on the distribution of pinning centers or on the repartition of CDW domains. The critical electric fields are strongly impurity dependent. The depinning at low temperature involves two critical fields : the first one where low frequency noise is generated without change in dV/dI that we interprete as depinning of individual domains and a second one where dV/dI drops. Finally the depinning by an ac field reveals new result's and that

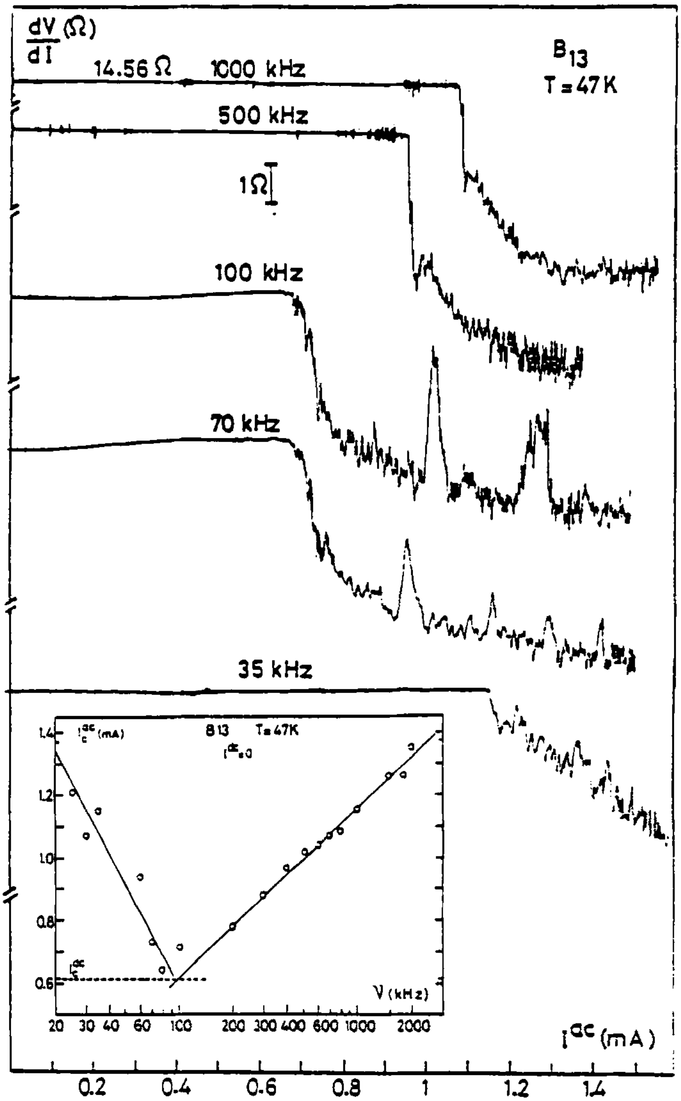

FIGURE 4 Variation of the differential resistance dV/dI (at 33 Hz) when the amplitude (in rms values) of an ac current is swept in the sample at different frequencies. The insert shows the variation of the critical current I_c^{ac} as a function of the frequency. I_c^{dc} is the critical current when a dc current is swept in the sample.

long relaxation times must be included in the understanding of the dynamics of the CDW in $NbSe_3$.

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