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CHARGE DENSITY WAVE DEPINNING AND SWITCHING IN $NbSe_3$

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We have investigated the relation between charge density wave (CDW) depinning and switching in $NbSe_3$. In the lower CDW state we observe that the critical electric field at which switching occurs is independent of temperature. We also observe that the differential resistance of the sample is independent of applied dc bias beyond the switching threshold, and corresponds to the high-field limit of the pure resistance. We interpret our results in terms of a temperature dependent CDW domain structure in the crystal.

It is by now well established that the highly non-linear conductivity observed[1] in the charge density wave (CDW) states of $NbSe_3$ is due to collective motion of the CDW condensate. Differential conductivity studies[2] have demonstrated a well-defined threshold electric field E_T for the onset of non-linear CDW conduction, with roughly the same characteristic temperature dependence in both the upper and lower CDW states. E_T reaches a minimum near the low-field resistivity maximum, increases with decreasing temperature T below this point, and diverges as T approaches the transition temperature T_p from below[3]. For an incommensurate CDW as in $NbSe_3$, a finite threshold field exists due to impurities randomly distributed throughout the crystal. For CDW conduction or "depinning" to occur, the impurity pinning potential must be overcome by the applied electric field.

Although the precise form of the dc current-voltage (I-V) characteristics near and above E_T in $NbSe_3$ varies somewhat from sample to sample, in most cases the non-linear conductivity is well described by the empirical formula[3]

$$\sigma(E) = \sigma_a + \sigma_b \exp\{-E_o/(E-E_T)\} \qquad (1)$$

where σ_a represents the low field (normal) conductivity, and σ_b and E_o are free parameters. In some $NbSe_3$ samples, however, sharp changes are observed in the differential conductivity near E_T[4], and Eq.(1) is not well obeyed. Drastic deviations are realized in samples which display hysteretic switching[5], where an actual jump occurs in the I-V characteristics at threshold. Switching may occur in $NbSe_3$ samples either voltage or current driven, and it occurs predominantly at temperatures below 30 K.

We have investigated the switching process and its relation to CDW depinning in $NbSe_3$. We find that "conventional" CDW depinning and switching are essentially independent processes, with different characteristic threshold fields and temperature dependences. Switching does, however, correspond to CDW motion. We also observe that the differential resistance of a switching crystal is independent of dc bias for fields exceeding the critical switching threshold E_T. The differential resistance thus obtained in the non-linear regime is only slightly temperature dependent, and corresponds to the saturated, high-field limit of the pure dc resistance. We speculate that these results are due to domain correlations in the specimen, where surface pinning plays an important role.

We have prepared crystals of $NbSe_3$ by direct reaction of the elements at 700 °C. The nominally pure samples, of typical dimensions 1 μm x 5 μm x 5 mm, have minimum threshold fields approximately 40 mV/cm.

Fig. 1 shows several I-V curves for a single $NbSe_3$ crystal at selected temperatures in the lower CDW state. This data was obtained by driving the sample with a nearly ideal voltage source. For the higher temperature data of Fig. 1, the threshold field E_T for CDW depinning is indicated by an arrow. E_T marks the first deviation from ohmic current response. As the temperature is lowered from approximately 53 K to 45 K, E_T increases smoothly, consistent with earlier studies[3]. However, at 45 K a strong "knee" has developed in the I-V characteristics somewhat above the CDW depinning threshold. A similar knee feature was first oberved by Monceau et al[4] in a detailed study of the differential resistance of $NbSe_3$. As the temperature is reduced below 45 K, Fig. 1 shows that E_T moves toward the knee. At the same time, the knee becomes sharper, and eventually, somewhat below 42 K, it describes a switching phenomenon[5]. For a particular sample at temperatures below 42 K, the switching occurs at the same voltage bias, independent of temperature. For applied fields exceeding the switching threshold E_c non-linear dc conduction is observed, and in related studies[6] we have also observed narrow-band noise and broad-band noise immediately following the switching.

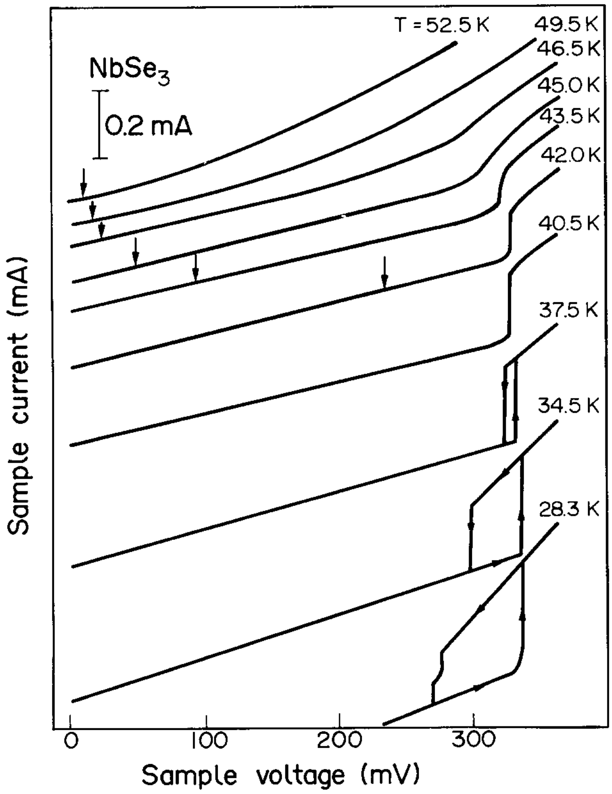

Fig. 1. dc I-V characteristics (voltage driven) for a $NbSe_3$ crystal at selected temperatures. The initial CDW depinning threshold E_T is indicated by an arrow for temperatures above 42 K.

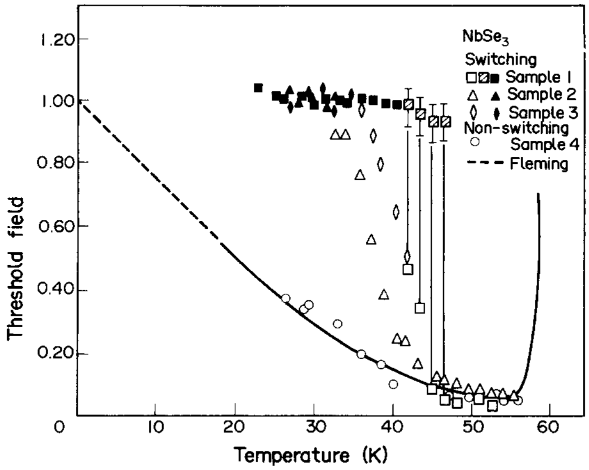

Fig. 2. Normalized threshold field for CDW depinning in $NbSe_3$. The open symbols represent a smooth threshold E_T, while solid symbols represent E_c for sharp switching. The hatched squares represent switching in the already non-linear CDW region; the corresponding E_T's are indicated at the bottom of the vertical lines. Solid curve is from ref. 3.

Hence, the CDW is depinned and in motion following the switching, as it is following the smooth threshold at E_T at higher temperatures.

Fig. 1 suggests that the temperature dependence of the threshold for CDW depinning is drastically different for $NbSe_3$ samples which display switching than for samples which do not display switching. This fundamental difference is illustrated more clearly in Fig. 2. Fig. 2 shows, as a function of temperature, the critical field for CDW depinning in various $NbSe_3$ samples. Samples which show switching and samples which do not show switching are represented. Also shown is E_T as determined by Fleming[3] for non-switching samples. We have normalized all data in Fig. 2 to the temperature independent switching threshold E_c. Fig. 2 shows two types of critical behavior. Non-switching samples from our preparation batches follow closely the temperature dependence of E_T as determined by Fleming[3], while samples which switch at lower temperatures show a more rapid increase in E_T with decreasing temperature somewhat below 50 K. In the later samples the critical field becomes independent of temperature as soon as switching commences. Below approximately 40 K the normalized switching threshold E_c is greater than E_T measured for non-switching samples. The low-temperature data of Fig. 2 was verified by a voltage pulse method[5], which eliminated the possibility of sample heating effects.

Again using a voltage pulse method[5], we have determined that at temperatures above approximately 40 K (depending on sample) the switching may still occur even though the depinning threshold E_T has already been exceeded. Thus switching is not always associated with the initial depinning of the CDW condensate. However, even in the non-linear region, switching still occurs (within experimental error) at the same critical switching field E_c determined at low temperatures. From Fig. 2 we see that the conventionally smooth depinning process at E_T and the switching at E_c may be viewed as independent processes, with the switching critical field quite independent of temperature. It is rather remarkable that two $NbSe_3$ samples from the same preparation batch, having roughly the same E_T near 50 K, may have drastically different critical behaviors at lower temperatures.

In addition to measuring the dc I-V characteristics by continuous dc or pulse method, we have investigated the differential resistance dV/dI near the critical switching field E_c by lock-in detection. Fig. 3 shows dV/dI as a function of current bias for a $NbSe_3$ sample at T = 28 K. Ohmic response is oserved up to the critical switching field at E_c. Above E_c, dV/dI is independent of dc bias, although the actual resistance R= V/I decreases with increasing bias in this region. We have observed this behavior in all $NbSe_3$ samples which display clear switching. An interesting

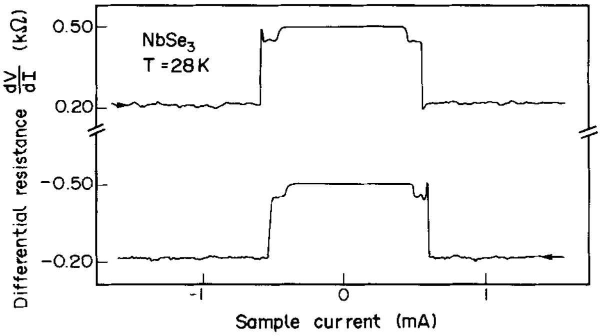

Fig. 3. Differential resistance dV/dI for $NbSe_3$ at T = 28 K. This sample displays sharp switching. The differential resistance is independent of electric field before and after the switch. Data for both forward and reverse current sweeps is shown.

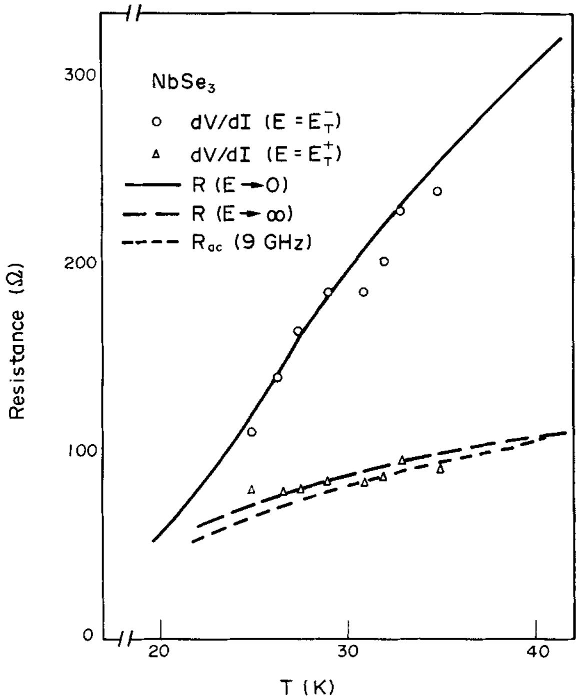

Fig. 4. Differential resistance dV/dI for $NbSe_3$ before and after switching. Also shown are the high field and high frequency limits of the resistance (refs. 1,7).

point is that dV/dI, following the switching, corresponds to V/I in the high field limit. In other words, immediately after the switch, the differential resistance corresponds to the saturated value of the pure resistance. This feature of the switching is illustrated in Fig. 4, where dV/dI, measured immediately before and after the switching, is plotted as a function of temperature. Also shown on the figure is the low-field (ohmic) resistance of the sample, and the high-field and high-frequency limits of the resistance as determined in other studies[1,7]. The differential resistance would then suggest that, at E_c, the sample switches to the "high-field conductivity state". We stress however that this applies to the differential conductivity, not the conductivity itself.

Our above observations demonstrate that switching dictates fundamental differences in the electric field and temperature dependence of the CDW depinning threshold, when compared to "conventional" CDW depinning without switching. It is interesting to note that early studies[8] of CDW depinning in $NbSe_3$ found a temperature independent threshold field E_T in the lower CDW state. At the time, this temperature independence was attributed to "locking" of the two CDW's present in $NbSe_3$ at low temperatures. However, the rapid increase in the depinning threshold field of the higher state CDW as the second transition is approached makes such an interaction unlikely. We find no evidence for CDW locking in samples which display switching or samples which do not display switching.

It has been suggested that switching in $NbSe_3$ is due to a coupling of individual CDW domains to form a coherent current-carrying state[5]. This idea has been further developed by Joos and Murray[9], who propose a model in which a $NbSe_3$ crystal is viewed as a ribbon of CDW domains, each domain being either in a conducting or non-conducting state. The probability of a single domain switching from the non-conducting state to the conducting state is determined by the state of its neighbors and the local electric field. Once a domain is conducting, a runaway process can result, eventually opening a conducting channel through the crystal. The macroscopic switch is complete when the channel has spread across the width of the specimen. In this model the sample dimensions and impurity concentration play important roles.

For $NbSe_3$ it is unclear which sample parameters dictate the switching process. We have however noted a general trend in that samples which switch often have a large length to cross-sectional area ratio, or, equivalently, a large surface to volume ratio. Hence surface pinning of the CDW condensate may play an important role in switching. The concentration and/or distribution of impurities may also contribute. Although we have not observed a strong correlation between impurity concentration (as determined by E_T at higher temperatures) and switching in relatively pure $NbSe_3$ specimens, Everson and Coleman[10] have demonstrated that multiple switching in $NbSe_3$ may be induced by moderate iron doping.

In terms of a domain approach, our experimental results suggest that domain structure becomes more rigid with lowering temperature in $NbSe_3$, although the depinning field for a single domain remains temperature independent. At high temperatures the distribution of uncorrelated domains is not uniform, with a larger concentration being found near the crystal surface. Here depinning near

E_T would involve CDW states near the central axis of the crystal, while surface states remain pinned until E_c is exceeded. This would lead to switching in the non-linear region. With decreasing temperature, the uncorrelated domain framework could grow steadily, finally approaching the model of Joos and Murray[9]. At low temperatures CDW depinning would correspond to sharp switching, with a sharp threshold, as observed. Whether such a description is consistent with our differential conductivity results however remains to be seen.

We finally remark that domain formation has been considered in the analysis of critical behaviors observed recently in the blue bronze $K_{0.3}MoO_3$[11]. Our experiments on $NbSe_3$ would suggest that the unusual temperature dependence of E_T in the blue bronze[11] may well be related to the observed switching phenomena.

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