DRIFT AND DIFFUSION IN MOVING CHARGE-DENSITY WAVES IN NIOBIUM TRISELENIDE: EVIDENCE FOR MOTION THROUGH THE GLIDE OF DISLOCATIONS ?

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ABSTRACT

A study has been made of the propagation of disturbance along moving charge-density waves in $NbSe_3$. The results indicate that the Frohlich currents conveyed by the CDWs which form at 144K and 59K are, in effect, carried respectively by positive and by negative charges, in each case with drift velocity much greater than the expected mean velocity of the CDW. It is proposed that motion of the CDW requires the glide along the specimen of dislocations, formed where the CDW adjoins stationary (possibly surface) layers of slightly different wavevector.

INTRODUCTION

Frohlich conduction, in which electrons move collectively as a charge-density wave (CDW), occurs in a few quasi low-dimensional metals in fields stronger than a threshold E_T, which originates in the "pinning" of the incommensurate CDW by crystal defects [1]. The conduction is commonly discussed in terms of the Fukuyama-Lee-Rice (FLR) model [2,3], whereby the CDW becomes pinned to randomly-distributed impurities by deforming elastically, and moves past them by "sliding", either as a continuous elastic body or, in a strong-pinning version recently proposed [4], by collapsing in their immediate vicinity.

The measurements briefly reported here, of the propagation of disturbance along moving CDWs in $NbSe_3$, provide a test of the FLR model. The experiment is analogous in principle to that by which Haynes and Shockley [5] detected the drift of minority carriers in semiconductors.

EXPERIMENTAL METHOD

The measurement uses terminals as in figure 1. A steady current I_1 keeps the CDW between *A* and *E* in motion, which motion is disturbed by a pulsed current I_2 superposed in segment *AB*. The effect on the Frohlich current I_c in segments *CD* further along the specimen is observed, using a bridge to record the departure of the voltage across *CD* from its Ohmic value.

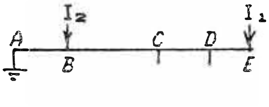

Figure 1.

If the CDW behaves, in accordance with the FLR model, as an elastic medium with frictional damping, the velocity imparted by I_2 will spread in a diffusion-like way along the moving CDW. The mean velocity V with which the effect of small I_2 propagates in the laboratory frame is then the drift velocity V_c which I_1 imposes on the CDW. The associated redistribution of Frohlich current is expressed by a linear equation of the usual form for combined diffusion and drift. The effective diffusivity D is easily shown to be K dV_c/dF, where K is the elastic modulus of the CDW, and F the force per unit volume exerted on it by I_1.

The propagation of disturbance has now been observed in three $NbSe_3$ specimens, with similar results. Cross-sectional areas A were ~ $100\mu m^2$, resistance ratios (300K/4.2K) ~ 70, and E_T ~ $200 mVcm^{-1}$ at 120K, ~ $50 mVcm^{-1}$ at 45K. Terminals (In, 0.2-0.5mm apart) were narrow (<20μm) to avoid phase slip at *B*, *C* and *D* (whose effect on measurement of V appeared small).

RESULTS

Records of the response of I_c to small I_2 appear in figure 2. The pulsed waveform of I_2 is shown at a, and the response of I_c in successive segments

(received October 27, 1989)

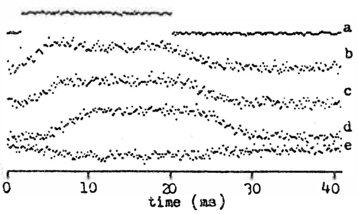

Figure 2. The response of I_c to I_2. The pulsed waveform of I_2 is shown at a. Records b, c and d show I_c observed respectively with X = 0.47, 0.67 and 0.93mm.

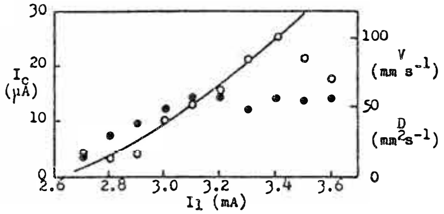

Figure 3. Drift velocity V (○) and effective diffusivity D (●) measured at 85K. The continuous line shows the Frohlich current I_c associated with I_1.

CD of the same specimen at b, c and d. The records, from the CDW with onset temperature T_c = 144K, were made with I_1 and I_2 flowing conventionally from *A* towards *E*. The spread of disturbance along the specimen is clearly apparent, though its diffusive component conceals the effect of drift: the ratios X/τ ($0.2\,\mathrm{ms}^{-1}$ in d), where X is distance from *B* to the mid-point of *CD*, and τ the delay in the response of I_c, over-estimate V.

The effect of drift is more clearly evident in records d and e. These refer to the same *CD*, but differ in the direction of I_1 and I_2, and thus of V. The much greater effect of I_2 in d implies that the drift was then from *A* to *E*, i.e. in the same direction as the conventional current. Thus the Frohlich current appears in this case to be carried by positive charge. The opposite result has been obtained from the CDW with T_c = 59K: at 40K the associated Frohlich current appeared to be carried by negative charge. This difference between the CDWs has been seen in all 3 specimens examined.

In estimating V and the effective diffusivity D from records such as those in figure 2, D was first found from the delay τ in the response of I_c for small X. V could then be found from the effect of reversing I_1 and I_2 (reversal of V is expected to change the steady state response of I_c by a factor exp[VL(1-a)/D], where L is the distance *AE*, and a = *AB*/L).

The values of V and D thus measured for the 144K CDW are shown as a function of I_1 in figure 3. The Frohlich current I_c induced by I_1 is also shown. For the 59K CDW, while V and D were clearly of the same order of magnitude as in figure 3, measurement was unreliable on account of current-induced changes in the low-field resistance.

For $I_1 < 3.4$mA (above which complications perhaps due to phase-slip appear), V is approximately proportional to I_c, giving a ratio VA/I_c = $6.4\mathrm{x}10^{-7}\mathrm{m^3C^{-1}}$ between drift velocity and Frohlich current density. The diffusivity D varies roughly as dI_c/dI_1, as would be expected.

COMPARISON WITH FLR PREDICTIONS

The inadequacy of the FLR model is already obvious, in the finding that Frohlich current appears be carried by positive charges in the case of the 144K CDW. Since all the relevant bands are about $^1/_4$ full, drift of either CDW as a whole should be in the sense appropriate to negative charge.

Apart from the discrepancy in sign, the drift velocity V for the 144K is about two orders of magnitude greater than if it referred to the sliding of the CDW as a whole. For such motion one would expect $VA/I_c = 1/\rho$, where ρ is the charge density concerned in the CDW; quarter-filling of a double band gives $1/\rho = 3.2\mathrm{x}10^{-9}\mathrm{m^3C^{-1}}$, or about $5\mathrm{x}10^{-3}$ of VA/I_c observed.

Values of D, however, are roughly as the FLR model predicts: they agree in order of magnitude with K dV_c/dF, based on an estimate of the screened elastic modulus for the CDW, with dV_c/dF derived from the observed dI_c/dI_1.

DISCUSSION

Clearly, V is not the velocity at which the whole CDW slides. Neither, in view of its sign for the 144K CDW, can it refer to sliding in narrow filaments (of which, in any case, there was no evidence). Its magnitude and diversity of sign are explicable, however, if V refers to the motion of dislocations in the CDW (or, in principle, of discommensurations, but the presence of these in $NbSe_3$ can be discounted [6]).

Although the role of dislocations in CDW transport has been considered by many authors (including Lee and Rice [3]), experiments have given few indications of their presence, except near current terminals and other barriers where phase-slip may involve dislocation climb. However, the recent observation by Csiba et al. [7], of the propagation of voltage noise in $Rb_{0.3}MoO_3$, seems to be evidence of the translation of a CDW being effected through the glide along the crystal of dislocation loops.

An explanation of the present results in similar terms is now proposed. As Frohlich current appears almost at once when a field $E > E_T$ is applied, one must suppose that in $NbSe_3$ such dislocations are present intrinsically, though during sustained conduction they are created at one current terminal and destroyed at the other. A model having the required properties can be constructed by assuming the dislocations to arise where the moving CDW, of equilibrium wavevector q_o, adjoins stationary layers (provisionally assumed to border the crystal surface) having a slightly different wavevector q_1. Motion of the CDW in the interior with velocity V_c then requires the dislocations to have velocity $V_D = V_c q_o/(q_o - q_1)$, much greater in magnitude than V_c, and of opposite sign if $q_o < q_1$.

It is suggested that the present experiments measure, in effect, the drift of a dislocation array of this type. So that observed drift velocity V (for the propagation of changes in V_c) may approximate to V_D (essentially a phase velocity), one must assume that the pinning and damping forces on the moving CDW are exerted through the dislocations at its boundaries (this leads to an apparent pinning by the crystal surface, consistent with some recent observations). If the thickness of the moving CDW is large compared with spacing of the dislocations, but small compared with the scale over which that spacing varies, the elasticity of the CDW confers on the dislocation array an effective elastic modulus $K_D = K(|q_o - q_1|)/q_o$. The diffusivity $D = K_D\, dV_D/dF$ is then the same as the FLR value $K\, dV_c/dF$.

Thus the model can account for the observed values both of V and D. In the case of the 144K CDW, stationary surface (or other) layers having $q_1 = 1.01 q_o$ would give V of the magnitude and sign observed; for the 59K CDW, the layers are required to have q_1 slightly less than q_o. In each case q_1 is slightly closer to the commensurate value $0.25b^*$ than is q_o.

The extent to which the above behaviour, seen in 3 specimens of one material, is a general feature of Frohlich conduction remains to be seen. Clearly, if it proves to be of widespread occurrence, a re-interpretation of the experimental data will be necessary in most areas of CDW transport.

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