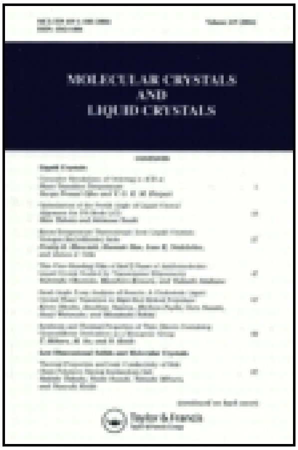

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PHASE VORTICES AND CHARGE DENSITY WAVE CONDUCTION NOISE

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Abstract Carrier conversion from the charge-density-wave (CDW) condensate to quasi particles should occur at the interface between moving and stationary CDW regions. This conversion is effected by moving phase vortices transverse to the advancing CDW. The present model predicts both the local origin of the narrow band noise and the amplitude of voltage oscillation. The effect of a thermal gradient on the noise frequency also provides support for this model.

INTRODUCTION

One of the most interesting features of electron transport in the series of compounds that exhibit charge-density wave (CDW) conduction is the appearence of well defined voltage oscillation[1] when the electric field exceeds a threshold field E_T. The fundamental frequency of this oscillation is proportional to the current carried by the moving CDW[2]. This phenomenon has been observed in $NbSe_3$, TaS_3 (orthorhombic and monoclinic), $(TaSe_4)_2I$, $(NbSe_4)_{3.33}I$ and the molybdenum bronzes $K_{0.3}MoO_3$ and $Rb_{0.3}MoO_3$, all of which display nonlinear I-V curves associated with CDW pinning[3]. Many current theories[4,5,6] consider the interaction of the moving CDW with impurities as the source of the voltage oscillations ("narrow band noise".) These theories imply that the voltage oscillation has a bulk origin.

In a recent paper[7] it was shown that in most of the experiments the contact introduces a large perturbation on the current flow of the moving CDW. In particular, if the contact silver paint envelops the sample the CDW is pinned in the region under the paint because the electric field E is small in this region. In uncovered regions E is large so that the CDW is depinned. Thus the contact truncates the sample into segments with independently moving CDWs separated by regions in which the condensate is pinned. Near the contact there exists an interface S which separates the moving CDW from the stationary CDW[8,9]. At S phase accumulates because of the advancing CDW on one side and phase slippage must occur to relieve the accumulation. (At the same time conversion of condensed to free quasi-particles must also occur at S.) Therefore it is quite natural to associate the origin of the conduction noise with the mechanism of conversion at the interface S. The phase accumulation that occurs at S is relieved by a train of phase vortices (or dislocations in the superlattice)[8] moving transverse to the advancing CDW. Due to phase conservation the product of the vortex velocity v_V and the vortex (linear) density n_V is related to the sliding velocity of the advancing CDW by

$$v_V n_V = v/\lambda_{CDW} = f \tag{1}$$

where f is the fundamental of the noise frequency.

PHASE VORTEX AS CURRENT CONVERTER

Let us adopt the following geometry. The CDW current is along x. A vortex parallel to the z axis moves with velocity v_V along the y axis so that it sweeps out the yz plane at x=0. We ignore sample boundaries for the moment. Then the vortex may be described as

$$\phi(x,y,t) = \tan^{-1}((y-v_V t)/x). \tag{2}$$

(Here we consider only the isotropic case, as the effect of anisotropy is easily eliminated by a scale change[10].) Substituting

Eq.(2) into the expressions for the CDW charge and the CDW current

$$\rho_{CDW} = en_s Q_{-1}\ \partial\phi/\partial x \tag{3}$$

and

$$J_{CDW} = -en_c Q^{-1}\ \partial\phi/\partial t \tag{4}$$

where n_s, n_c and Q are the CDW charge density, the condensate density and $Q = 2k_F = 2\pi/\lambda_{CDW}$, we obtain;

$$\rho_{CDW} = en_s Q^{-1}\ (y-v_V t)/(x^2 + (y-v_V t)^2) \tag{5}$$

and

$$J_{CDW} = en_c Q^{-1}\ v_V x/(x^2 + (y-v_V t)^2) \tag{6}$$

Equation 5 implies that the phase vortex does not carry a net electric charge (i.e. the space integral of Eq. 2 vanishes) but, instead, an electric dipole moment in the y direction. Eq.(6) means, on the other hand, that the phase vortices are the source of an electric current. Integrating Eq.(6) over y, we find that a single phase vortex sends out an electric current equal to $\pi en_c Q^{-1} v_V = 1/2\ en_c v_V\ \lambda_{CDW}$ in both $\pm$ x directions. When the CDW in the region x>0 is advancing with velocity v in the -x direction, and the CDW is stationary in the region x<0, the total J_{CDW} generated by phase vortices cancels exactly the J_{CDW} due to the sliding CDW (provided the vortex density satisfies the phase conservation in Eq. 1.) On the other hand, in the region x>0, where there is no CDW current the phase vortexes send out exactly the same amount of electric current. Therefore the phase vortices effect the conversion of the CDW current into the quasi-particle current. Furthermore the phase conservation guarantees the conservation of the total current $J_{tot} = J_{CDW} + J_n$ at the boundary. In spite of this conservation, phase vortices introduce a spatial nonuniformity of the electric current, as the current sources are fairly localized. When a train of vortices moving in the y direction forms a regular lattice (this will happen when the inter vortex distance becomes less than the transverse Fukuyama-Lee-Rice length[10], L, which is of the order of 30 to 50 μm for clean $NbSe_3$ samples), this provides the source of quasi-particle current which changes periodically in time with frequency f. The amplitute of the voltage oscillation due to one phase vortices may be estimated as follows

$$\Delta V = (1/2)en_c\, \lambda_{CDW} v_V \rho\, L_t/a \qquad (\text{for } L_t < a)$$

$$= (1/2)en_c\, \lambda_{CDW} v_V \rho \qquad (\text{for } L_t > a) \qquad (7)$$

where a is the transverse dimension of the sample (thickness in the y direction), L_t is the transverse Fukuyama-Lee-Rice length and ρ is the normal resistivity of the sample near the contact. Here we have assumed that the influence of a phase vortices is screened within the distance of L. The predicted ρ and a^{-1} dependence of the ac voltage amplitude are in semi-quantative agreement with experiments[12] on $NbSe_3$ and TaS_3.

THERMAL GRADIENT EXPERIMENT

We now discuss the result of imposing a thermal gradient on the sample and studying its effect on the noise spectrum[11]. This provides a rather clear demonstration of the local origin of the voltage oscillations. As usual the current is held constant in a two-probe sample and oscillations in the voltage are monitored in a spectrum analyser. One end of the sample A is kept at a fixed temperature T_A while the other end is heated by an amount $\Delta T = T_B - T_A$ (Fig. 1.) As ΔT is increased from zero the single fundamental frequency in the noise splits into two fundamental frequencies f_1 and f_2. More significantly, one of the frequencies (f_1) stays at

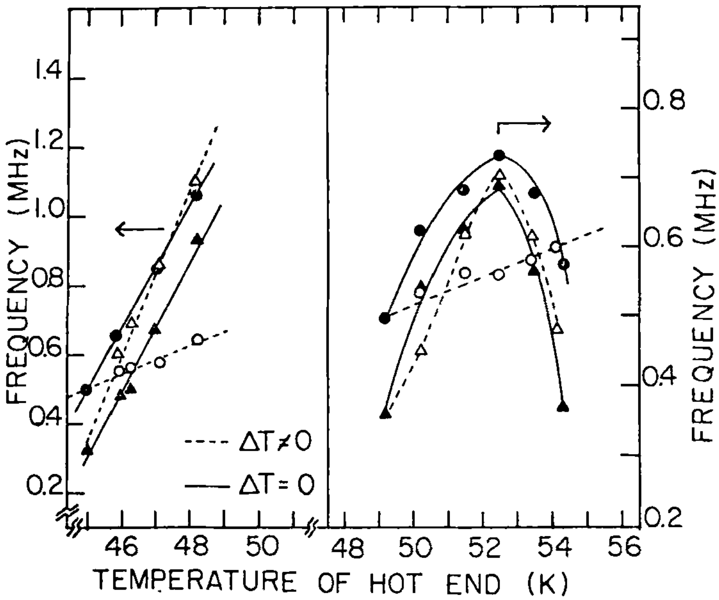

FIGURE 1 Plot of frequency f vs. temperature of hot end T_2 for a fixed sample current in $NbSe_3$. In both panels the solid lines and solid symbols indicate variation of f as the sample is uniformly heated; the broken lines and open symbols indicate variation of f when the cold end is clamped nominally at 45 K (left panel) and 49 K (right panel) while the hot end is heated. Circles (triangles) refer to the fundamental frequency f_1 (f_2). Note the strikingly different trajectories of f_1 and f_2 in the right panel.

the fixed value appropriate to the fixed temperature T_A while the other f_2 moves up or down with ΔT, depending on the value of T_B. If T_B is below 52 K (the temperature at which the single frequency in a uniformly heated sample attains a maximum value) f_2 increases with T_B; if T_B exceeds 52 K f_2 decreases to zero. Thus an unambiguous identification of f_1 with end A and f_2 with end B can be made. Furthermore, when end B is heated past the transition temperature at 59 K f_2 vanishes and the remaining f_1 assumes the value appropriate to the cold end of the sample. (See Ref. 11 for more details.)

The temperature gradient dependence of the fundamental frequencies is most readily interpreted if there are a train of phase vortices at each end generating the voltage oscillations. Furthermore, for a given total current through the sample the velocity of the sliding CDW at each end is determined by the value of E_T at that end which depends on the local temperature. In the uniformly heated sample E_T is the same at both ends and therefore $f_1 = f_2$. (In recent experiments[11] we have shown that if the sample length is short enough f_1 remains locked to f_2 until the gradient exceeds a certain value.) Therefore in the uniform situation the velocity of the CDW is uniform and phase slippage is required at the ends. In a thermal gradient large enough to split the fundamental frequency the velocity jumps abruptly from zero at one end, increases uniformly to the value at the other end, and then abruptly vanishes. To accomodate the constantly changing velocity in the bulk, conversion to free carriers must occur in the bulk (possibly by nucleation of dislocations as well.) However, this bulk conversion does not produce narrow band noise. If the bulk conversion proceeds by periodic nucleation of phase vortices the phase slip frequency which is proportional to the velocity difference between adjacent regions would be vanishingly small.) The prominent oscillations observed experimentally are associated only with the abrupt changes in velocity at the sample ends.

CONCLUSION

We have shown that phase vortices are generated at the boundaries where the CDW's with different sliding velocity meet. Since the phase vortex converts the CDW current into normal current or vice versa, a moving phase vortex gives rise to voltage oscillations observed in experiments in which the current is held constant. This model accounts for the local origin of the noise. Although our model has some similarity to a model proposed by Gor'kov[9] there are some important differences. For example we have emphasized the role of the free carriers in coupling the phase slippage to fluctuations in the conductive voltage which the experimentalist measures. We also believe that Gorkov's model applies only to extremely thin samples with transverse dimensions of the order of microscopic coherence distance (~2 nm.) In his model the transverse spatial dependence of the CDW order parameter is completely neglected. On the other hand, in this particular limit his model has the advantage that the phase slips may be formulated from the microscopic theory.

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