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MODEL OF DYNAMIC CHARGE DENSITY WAVE BREAK-UP IN AN APPLIED TEMPERATURE GRADIENT

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ABSTRACT

We examine theoretically the high-velocity dc dynamics of a charge density wave (CDW) condensate subjected to a uniform longitudinal temperature gradient. The condensate is treated within an elastic medium model where internal strain and carrier conversion are treated explicitly. For sufficiently large temperature gradients, the CDW breaks up into a series of N coexisting subdomains with independent phase velocities. N scales directly with the magnitude of the temperature gradient and with the length of the crystal. Unusual dynamical asymmetries are also predicted depending on the relative directions of heat and electrical current flow through the CDW crystal.

INTRODUCTION

It is known experimentally that a longitudinal temperature gradient applied to a crystal supporting a sliding charge density wave (CDW) condensate can "break" the condensate into "subdomain" regions with independent CDW phase velocities v_0 [1]. This break-up reflects a competition between the tendency for macroscopic CDW phase velocity coherence and the tendency for the CDW velocity to assume a distribution of values dictated by local conditions.

We here examine theoretically the dc velocity profile (i.e. subdomain structure) of a CDW conductor in a temperature gradient. In the high velocity limit ($E \gg E_T$), the total number of subdomains present in the crystal, N, scales with the temperature difference ΔT across the ends of the crystal and with the

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length L of the crystal: $N \sim \Delta T^{2/3} L^{1/3}$ in one limit, and $N \sim \Delta T^{2/5} L^{3/5}$ in another limit.

MODEL

The CDW is modeled as an elastic medium subject to temperature gradient induced internal strain, where excessive strain is relieved by the formation of multiple velocity subdomains whose boundaries comprise phase slip centers (PSC's). The position dependent charge density is given by the usual expression $\rho(x) = \rho_o + \rho_1 \cos[Qx + \Phi(x,t)]$ where $Q=2k_F$ and $\Phi(x,t)$ is the CDW phase. For a given region where the CDW velocity is constant (i.e. for a given subdomain), $\Phi(x,t) = Qv_o t + \phi(x)$ where $\phi(x)$ is a (time independent) distortion. x=0 lies in the center of the sub-domain. The temperature variation across the sub-domain and the constraint that v_o be uniform lead to a position-dependent internal elastic strain $s(x) \equiv (1/Q)d\phi(x)/dx = \Delta Q/Q$, which in turn leads to position-dependences in the CDW wavevector, charge density, and damping. Within a sub-domain, the CDW equation of motion is [2]

$$\frac{\gamma(x)}{Q}\frac{d\Phi}{dt} - \frac{1}{Q}\frac{d}{dx}\left(\kappa(x)\ \frac{d\Phi}{dx}\right) = \rho_o(x)\ E(x) \tag{1}$$

where γ and κ are the CDW damping and elasticity. We first solve self-consistently for v_o and the strain energy U_s of a given subdomain. The number of subdomains is then found by balancing the total strain energy against the total phase slip energy associated with subdomain interfaces.

Single subdomain velocity and strain energy

To first order the position dependences of κ and the applied electric field E result from the temperature variation T(x), while the position dependence of ρ_o is dominated by the strain ($\rho_o(x) \approx \rho_o - \rho_s s$); the damping has strain and temperature terms ($\gamma(x) \approx \gamma + \gamma'(\Delta T/L)x - \gamma_s s$). Eq. (1) leads to a sub-domain phase velocity

$$v_o = \frac{\rho_o E}{\gamma}\left[\frac{1 - \frac{L_D\ E'\ \Delta T}{2\ E\ L}\ \xi\left(\frac{E}{\varepsilon}\right)}{1 - \frac{L_D\ \gamma'\ \Delta T}{2\ \gamma\ L}\ \xi\left(\frac{E}{\varepsilon}\right)}\right] \tag{2a}$$

$$\xi(v) = \coth(v) - \frac{1}{v} \tag{2b}$$

$$\frac{E}{\varepsilon} \equiv v \equiv \alpha\frac{L_D}{2} = \frac{\rho_s\ E\ L_D}{2\ \kappa}\ (1-r) \tag{2c}$$

where $r = (\rho_o\gamma_s)/(\gamma\rho_s)$ and the primes denote temperature derivatives.

The associated sub-domain strain s(x) derived from Eq. (1) can be used to evaluate the phase strain energy U_s for the sub-domain:

$$U_s = \frac{1}{2}\int \kappa(x) \ |s(x)|^2 \ dx \approx \frac{\frac{\kappa}{2}\left(\frac{\rho_o}{\rho_s}\right)^2 \left(\frac{E'}{E} - \frac{\gamma'}{\gamma}\right)^2 \left(\frac{\Delta T}{L}\right)^2}{(1-r)^2 \left\{1 - \frac{L_D}{2}\frac{\gamma'}{\gamma}\frac{\Delta T}{L}\xi\left(\frac{E}{\varepsilon}\right)\right\}^2} \times$$

$$\left[\frac{L_D^3}{3} + \frac{L_D^3}{4}\operatorname{csch}^2(\nu) - \frac{3\,L_D^2}{2\,\alpha}\coth(\nu) + \frac{2\,L_D}{\alpha^2}\right]. \quad (3)$$

U_s increases with the size L_D of the subdomain.

<u>Number of subdomains</u>

The number of sub-domains N in the entire crystal is obtained by minimizing the total energy $U_{tot,N}$ of the crystal. For the entire crystal,

$$U_{tot,N} = (N-1)U_{ps} + \Sigma_i U_{si} \quad (4)$$

where U_{si} is the strain energy of the i^{th} subdomain, and U_{ps} is the energy associated with each phase slip center. Far from the Peierls transition temperature we may treat U_{ps} as being a constant, independent of temperature and position. Minimizing $U_{tot,N}$ leads to

$$U_{tot,N} = U_{ps}\ (N-1) + \frac{B_m\ (\Delta T)^2\ L^{m-2}}{N^{\ m-1}} \quad (5)$$

where B_m is a weak function and m=3 (or 5) in the large (small)-$|\nu|$ limit. The critical value of ΔT at which the total number of sub-domains in the crystal will change by one is determined from Eq. (5) by setting $U_{tot,N} = U_{tot,N+1}$, yielding

$$\frac{U_{s1}}{U_{ps}} = \frac{N^2\ (N+1)^2}{2N + 1} \qquad \text{(large } |\nu|) \quad (6a)$$

$$\frac{U_{s1}}{U_{ps}} = \frac{N^4\ (N+1)^4}{4N^3 + 6N^2 + 4N + 1} \qquad \text{(small } |\nu|). \quad (6b)$$

In the limit of large N, the number of sub-domains can be written in closed form:

$$N = \left(\frac{2\ U_{s1}}{U_{ps}} \right)^{\frac{1}{3}} = \left(\frac{2\ B_m\ [\Delta T]^2\ L}{U_{ps}} \right)^{\frac{1}{3}} \qquad \text{(large } |v|) \qquad (7a)$$

$$N = \left(\frac{4\ U_{s1}}{U_{ps}} \right)^{\frac{1}{5}} = \left(\frac{4\ B_m\ E^2\ [\Delta T]^2\ L^3}{U_{ps}} \right)^{\frac{1}{5}} \qquad \text{(small } |v|) \qquad (7b)$$

which demonstrates directly a surprising scaling between N and ΔT for fixed L, and between N and L for fixed ΔT.

Dynamical asymmetry

It is noteworthy that Eq. (2a), the expression for the CDW velocity v_o within a sub-domain, has an unusual asymmetry with respect to the signs of E and ΔT. If both ΔT and E are reversed, the equation remains invariant. On the other hand, if only ΔT or only E is reversed in sign, the expression for v_o is markedly different. The magnitude of v_o plays an essential role in determining N in Eq. (6). Hence, in the presence of a fixed temperature gradient, the model suggests that a different number of sub-domains can result depending on the relative directions of the electrical and heat currents in the sample. Furthermore, this phenomenon may be the cause of asymmetries observed in the noise spectra of some CDW conductors under isothermal conditions, where an inhomogeneous impurity distribution may manifest itself as (very loosely speaking) a "built-in" temperature gradient, with similar consequences.

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