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 $v_c[1]$. 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 ($v \gg v_c$), the total number of subdomains present in the crystal, N, scales with the temperature difference $\Delta T$ across the ends of the crystal and with the

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length \( L \) of the crystal: \( N \Delta T^{2/3} L^{1/3} \) in one limit, and \( N \Delta T^{2/5} L^{3/5} \) 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

\[
\rho(x) = \rho_0 + \rho_1 \cos(Qx + \Phi(x,t)) \quad \text{where} \quad Q=2k_F \quad \text{and} \quad \Phi(x,t) \quad \text{is the CDW phase. For a given region where the CDW velocity is constant (i.e. for a given subdomain),} \\
\Phi(x,t) = \nu_0 t + \Phi(x) \quad \text{where} \quad \Phi(x) \quad \text{is a (time independent) distortion.} \quad x=0 \quad \text{lies in the center of the sub-domain. The temperature variation across the sub-domain and the constraint that } \nu_0 \text{ be uniform lead to a position-dependent internal elastic strain } s(x) = (1/Q) \frac{d\Phi(x)}{dx} = \Delta Q/Q, \quad \text{which in turn leads to position-dependences in the CDW wavevector, charge density, and damping. Within a sub-domain, the CDW equation of motion is} \quad \text{(2)}
\]

\[
y(x) \frac{d\Phi}{Q dt} = \frac{1}{Q} \frac{d}{dx} \left( y(x) \frac{d\Phi}{dx} \right) - \rho_0(x) E(x)
\]

where \( \gamma \) and \( \kappa \) are the CDW damping and elasticity. We first solve self-consistently for \( \nu_0 \) 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 \( \kappa \) and the applied electric field \( E \) result from the temperature variation \( \gamma(x) \), while the position dependence of \( \rho_0 \) is dominated by the strain \( (\rho_0(x) = \rho_0 - \rho_0 s) \); the damping has strain and temperature terms \( \gamma(x) = \gamma + \gamma' (\Delta T/L) x - \gamma_s s \). Eq. (1) leads to a sub-domain phase velocity

\[
\nu_0 = \frac{\rho_0 E}{\gamma} \left[ \frac{1}{2} \frac{\Delta T}{L} \frac{\xi(\frac{v}{\gamma})}{\xi(\frac{v}{\gamma})} \right]
\]

\[
\xi(v) = \coth(v) - \frac{1}{v}
\]

\[
\frac{E}{\gamma} = \nu = \frac{\rho_0 E}{\gamma} - \frac{\rho_0}{\kappa} (1-r)
\]

where \( r = (\rho_0 \gamma_0)/(\rho_0 \gamma) \) 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:

\[
U_s = \frac{1}{2} \int k(x) \left| s(x) \right|^2 \, dx = \frac{k}{2} \left( \frac{E_0}{E} \right)^2 \left( \frac{E'}{E} - \frac{\nu'}{\nu} \right)^2 \left( \frac{A_{ps}}{L} \right)^2 \left( 1 - r \right)^2 \left\{ 1 - \frac{L_D \nu' \Delta T}{2 \gamma L} \xi \left( \frac{E'}{E} \right) \right\}^2 \left[ \frac{L_D^3}{3} + \frac{L_U^3}{4} \text{csch}^2(v) - \frac{3 L_D^2}{2} \frac{1}{\alpha} \coth(v) + \frac{2 L_D}{\alpha^2} \right].
\]

\( U_s \) increases with the size \( L_D \) of the sub-domain.

**Number of subdomains**

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,

\[
U_{tot,N} = (N-1)U_{ps} + \Sigma_i U_{si}
\]

(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

\[
U_{tot,N} = U_{ps} (N-1) + \frac{B_m (\Delta T)^2 u^{m-2}}{N^{m-1}}
\]

(5)

where \( B_m \) is a weak function and \( m=3 \) (or 5) in the large (small)-\( |V| \) limit. The critical value of \( \Delta T \) 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

\[
\frac{U_{si}}{U_{ps}} = \frac{N^2 (N+1)^2}{2N + 1} \quad \text{(large } |V|) \quad \text{(6a)}
\]

\[
\frac{U_{si}}{U_{ps}} = \frac{N^4 (N+1)^4}{4N^3 + 6N^2 + 4N + 1} \quad \text{(small } |V|) \quad \text{(6b)}
\]

In the limit of large \( N \), the number of sub-domains can be written in closed form:
\[
N = \left( \frac{2 \frac{U_{sc}}{V_p}}{V_p} \right)^{\frac{1}{3}} = \left( \frac{2 \frac{B_m}{} \frac{\Delta T}{T}^2 L}{V_p} \right)^{\frac{1}{3}} \quad \text{(large } |v| \text{)} \quad (7a)
\]

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

which demonstrates directly a surprising scaling between \( N \) and \( \Delta T \) for fixed \( L \), and between \( N \) and \( L \) for fixed \( \Delta T \).

**Dynamical asymmetry**

It is noteworthy that Eq. (2a), the expression for the CDW velocity \( v_0 \) within a sub-domain, has an unusual asymmetry with respect to the signs of \( E \) and \( \Delta T \). If both \( \Delta T \) and \( E \) are reversed, the equation remains invariant. On the other hand, if only \( \Delta T \) or only \( E \) is reversed in sign, the expression for \( v_0 \) is markedly different. The magnitude of \( v_0 \) 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 \textit{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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**REFERENCES**
