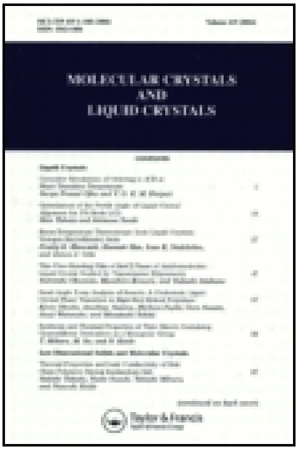

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Charge Density Wave Conduction Of Small Samples

Mark O. Robbin [a] & R. A. Klemm [a]

[a] Corporate Research Science Laboratories, Exxon Research and Engineering Company, Annandale, NJ, 08801

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CHARGE DENSITY WAVE CONDUCTION OF SMALL SAMPLES

MARK O. ROBBINS and R. A. KLEMM
Corporate Research Science Laboratories, Exxon Research and Engineering Company, Annandale, NJ 08801

Abstract The charge density wave dynamics of samples with dimension near the Lee-Rice coherence length were studied. In the high frequency and current limits the conductivity of such small samples approaches that of infinite samples. Finite size effects change the response at low frequency and current. A "kink" is introduced in dV/dI like that found experimentally in some $NbSe_3$ samples at low temperatures.

Intensive experimental investigation of conducting charge density wave (CDW) systems has revealed a wealth of interesting phenomena.[1] In this paper we report results of detailed theoretical studies of the CDW dynamics of small samples. The calculation is based on the classical model of an overdamped CDW pinned by weakly scattering impurities.[2,3]

The equation of motion for the local phase ϕ of the CDW is[2,3]

$$[\tau_0^{-1} \frac{\partial}{\partial t} - \nabla^2]\ \phi(r,t) = e^{*}E_Q + V\delta n(\vec{r})\sin[\vec{Q}\cdot\vec{r} + \phi(\vec{r},t)]\ , \quad (1)$$

where lengths have been scaled to make the equation isotropic and the velocity of phase excitations is set to one. The terms on the left of (1) are the damping force and the elastic force which limits distortions of the CDW. The terms on the right are the coupling to the component of the electric field along the CDW wave vector $\vec{Q}$ and the force contributed by impurities which have concentration c and local density $\delta n(\vec{r})$. The experimentally measured CDW current will be proportional to the time derivative of the collective coordinate Δ defined as the volume average of ϕ.

We consider the case of weak pinning[2] where $V<c^{-1/3}$ and $V<\lambda$ the coherence length for the CDW amplitude. For weak pinning the phase of the CDW varies on the scale of the Fukuyama-Lee-Rice[2] (FLR) coherence length $\xi \propto 1/(cV^2)$. For samples with dimension $L<\xi$, the spatial fluctuation of the phase $\delta\phi(\vec{r},t) \equiv \phi(\vec{r},t) - \Delta$ is a small parameter. Equation (1) can then be solved for Δ perturbatively or iteratively in terms of the Greens function for the differential operator on the left of (1) and the source term represented by the expression on the right.[3]

The differential operator in (1) describes diffusive transport. Thus $t_L \equiv L^2/\tau_0$ is the time for propagation over the sample dimension L. The response of a finite sample approaches the infinite volume limit for processes with time scale less than t_L, i.e., for a.c. fields with $\omega t_L > 1$ or d.c. currents where $\dot{\Delta} t_L > 1$. Therefore calculations for small samples reveal the large sample response on short time scales as well as indicating how finite size effects may be evidenced experimentally on longer time scales. Many samples are believed to have dimensions of order ξ.

Equations for $\dot{\Delta}$ were derived from (1) to second order in perturbation theory. The calculation is similar to that of Klemm and Schrieffer (KS),[3] except that nonadiabatic corrections are included in the results reported here. These corrections significantly affect the CDW dynamics. In this paper the field and frequency dependent conductivities are described.

The differential resistance dV/dI calculated as a function of d.c. field for a sample with $L=\xi/(2\pi)$ is presented in Fig. 1. Also shown are experimental results[4] for a 2mmX10μX10μ sample of $NbSe_3$ at 48K, and results from the Grüner, Zawadowski and Chaikin (GZC) model[5] of a rigid, overdamped CDW in a periodic potential. For comparison with experiment fields are normalized to the threshold field E_T and a parallel resistance due to normal electrons is included in the theoretical results. Note the dramatic agreement between the experimental data and the results of our calculation. In contrast, the GZC model predicts a monotonically increasing dV/dI which is never observed

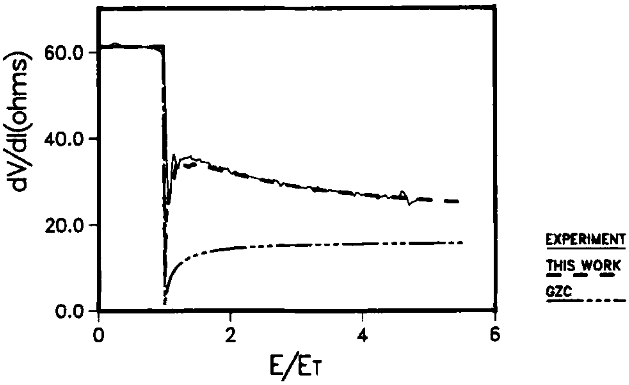

Figure 1. Differential resistance vs. field, see text.

experimentally. This discrepancy is due to the strong current dependence of the damping by internal elastic modes (phasons) of the CDW which is not included by GZC or KS.

The elastic damping produces a renormalized effective damping rate $\tau^{-1}(\dot{\Delta})$ which is larger than τ_0^{-1} and current dependent. In the moving frame of the CDW, impurities produce a periodic force with $\omega_p=\dot{\Delta}$. Only phasons with $\omega>\dot{\Delta}$ can respond to this force and contribute fully to the damping. As the current increases, fewer phasons respond and the damping rate decreases towards τ_0^{-1} as $\dot{\Delta}^{-1/2}$. This gives the asymptotic I-V relation $I=\sigma_\infty V-CV^{1/2}$ first derived by Sneddon, Cross and Fischer.[6] In finite samples the minimum energy of phasons is of order t_L^{-1}. For $\dot{\Delta}t_L<1$ all phasons can respond and τ^{-1} saturates at a constant value.

Although the approach here is limited to $L<\xi$, the results suggest how the behavior of dV/dI scales as $L\to\infty$. The behavior at threshold changes dramatically. The sharp fall and rise of dV/dI at threshold (Fig. 1) occurs in the field range where τ^{-1} is constant. As L increases, this range decreases and therefore the width of the "kink" decreases. Extrapolating to the infinite volume limit we find $\dot{\Delta}\propto(E-E_T)^{3/2}$ near threshold. The same exponent is found by Fisher.[7] A monotonic decrease in dV/dI above threshold is implied, which is observed in many samples. Our results suggest that the "kink" in dV/dI is a finite size effect and explain why it is seen in some samples and not in others. Indeed kinks in dV/dI tend to correlate with small sample size and low temperature where ξ is large.[8]

The renormalized relaxation rate for a.c. conductivity is the same as that for d.c. conductivity: $\tau^{-1}(\omega)=\tau^{-1}(\dot{\Delta})$. Both ω and $\dot{\Delta}$ represent the rate of change in Δ. This is the only factor determining which phasons contribute to the damping. The calculated $\sigma(\omega)$ is much broader than the single overdamped harmonic oscillator (OHO) response predicted by GZC. For $\omega t_L \gg 1$ we find $Re(\sigma(\omega)) \approx \sigma_\infty(1-C\omega^{-0.5})+\sigma_N$ and $Im(\sigma(\omega)) \approx \sigma_\infty C'\omega^{-0.5}$, where σ_N is the conductivity of the normal electrons. At low frequencies our model gives a response like an OHO, but with a renormalized damping time. As in the case of the d.c. conductivity this is a finite size effect. We suggest that in samples with kinked dV/dI characteristics the low frequency response will approach that of a rigid CDW. If our results are extrapolated to $L\to\infty$ we find the low frequency form of the dielectric constant is $\varepsilon(\omega)-\varepsilon(0)\propto(i\omega)^{0.5}$.

The non-adiabatic effects included in our calculation also lead to hysteresis and memory effects.[1] The response to combined a.c. signals is changed from the simple GZC result.[9] These topics are the focus of ongoing research.

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