

TEMPORALLY-ORDERED CDW CREEP IN PURE AND DOPED NbSe₃

K. Cicak, K. O'Neill, and R. E. Thorne

Physics Department, Cornell University, Ithaca, NY 14853-2501, USA

Abstract. Below $T = 40$ K, charge-density wave (CDW) transport in NbSe₃ exhibits two well-defined driving force thresholds E_T and E_T^* . Between these thresholds the CDW moves extremely slowly with creep-like temperature and driving force dependences. At the same time, the CDW exhibits coherent oscillations with a frequency proportional to the CDW current and having very narrow spectral widths, implying that the motion exhibits temporal order. We have extended our initial work to doped crystals containing isoelectronic (Ta) and nonisoelectronic (Ti) impurities and to crystals of different thicknesses. The functional form of the creep velocity versus driving force and temperature between E_T and E_T^* is consistent across all samples for velocities ranging over five orders of magnitude. The temperature dependence implies that motion is limited by processes with an energy scale comparable to the CDW gap. The field and impurity dependences are inconsistent with all proposed forms for CDW creep and with our earlier one impurity - one barrier picture. The abrupt increase in CDW velocity at E_T^* appears to be associated not with a characteristic field but a characteristic velocity, corresponding to a narrowband noise frequency comparable to the estimated frequency of thermal activation over local strong pinning barriers.

1. INTRODUCTION AND EXPERIMENT

At the last ECRYS meeting we reported the discovery of "temporally-ordered creep" in NbSe₃ and an analysis suggesting that the relevant barriers were associated with CDW amplitude collapse at individual impurities [1]. We have extended this work to crystals intentionally doped with isoelectronic Ta (~ 3 to 8×10^{18} cm⁻³) and nonisoelectronic Ti (~ 3 to 7×10^{17} cm⁻³) impurities and to crystals of varying thickness (~ 0.15 to 1.3 μ m), over the temperature range 15 K to 28 K. The accessible doping and temperature range is limited by ohmic heating effects at low temperature and for large E_T , and the upper thickness range is limited by the difficulty of finding thick, step free crystals with uniform current flow. For a partially gapped material like NbSe₃, the CDW current in the "slow branch" between E_T and E_T^* comprises a small fraction (10^{-9} to 10^{-5}) of the total current and cannot be measured directly. However, the motion is temporally ordered and the system exhibits coherent voltage oscillations (narrow band noise or NBN). The CDW velocity-field relation, $v(E, T)$, is then obtained by current-biasing a high quality NbSe₃ crystal and measuring the NBN frequency $f(E, T) = v(E, T)/\lambda_c = j_c(E, T)/n_c e \lambda_c$ where λ_c , j_c , and n_c are CDW wavelength, current density, and condensate density respectively, and e is the electron charge.

2. RESULTS AND CONCLUSIONS

E_T and E_T^* are well defined in all crystals in this temperature range by sharp increases of broad band noise (BBN). In addition, E_T^* is also characterized by a steep or discontinuous increase in CDW velocity. No NBN oscillations were observed below the collective threshold E_T . The CDW moves extremely slowly for $E_T < E < E_T^*$ with the smallest measured frequencies of 0.3 Hz just above E_T corresponding to a CDW velocity of ~ 4 Å/s. The oscillations display remarkably narrow spectral widths ($Q = f / \Delta f \sim 250$), signaling that the motion exhibits significant temporal coherence, and yet the extremely slow velocities, exponential field dependence, and activated temperature dependence are all characteristics of creep, confirming our original picture of temporally-ordered creep.

All of our $j_c(E,T)$ data sets, except for temperatures below 18 K where heating effects were significant, are found to be in excellent agreement with a modified Anderson-Kim form [2],

$$j_c = \sigma_0 (E - E_T) \exp[-T_0/T] \exp[\alpha(E - E_T)/T] \quad (1)$$

where σ_0 , T_0 , and α are fitting parameters, and where the subtraction of E_T from E reflects the fact that the internal force driving local CDW motion above E_T is $\sim E - E_T$ and not E . Figure 1 shows scaled data for eight crystals with different dopings and thicknesses at different temperatures and corresponding to more than 20 separate $f(E)$ measurements. The scaling of all data over more than 5 orders of magnitude in current suggests the robustness of the behavior in high-quality crystals and that the form (1) must be close to the correct functional form.

For all crystals, the fit parameter T_0 , interpreted as a microscopic creep barrier, is found to be $546 \text{ K} \pm 10\%$, independent of doping, thickness or temperature. This value corresponds to $\sim 1.4\Delta_c$ ($2\Delta_c$ is a CDW gap), consistent with expected barriers for local strong pinning [3] and supporting our earlier assertion that the microscopic events facilitating creep may involve local CDW amplitude collapse. We interpreted αE as a barrier reduction due to the applied field E , with $\alpha = en_c V_{\text{barr}} \lambda_c / k_B$ proportional to the volume per barrier V_{barr} . Our original data on undoped crystals suggested that V_{barr} was comparable to the estimated volume per impurity V_{imp} . In doped crystals α shows only a small change with doping, and so $V_{\text{barr}} \gg V_{\text{imp}}$. V_{barr} is still orders of magnitude smaller than the FLR domain volume. Consequently, the one impurity - one barrier picture is incorrect, but the scale of these barriers is still small compared with that for the collective dynamics responsible for the temporally ordered response.

What is the nature of the upper threshold E_T^* ? Our new data show that the fitting parameter α scales with E_T^* , $\alpha \propto (E_T^*)^{0.9}$. Further, our study shows evidence that the threshold field E_T^* should be attributed to existence of a threshold velocity v_T^* at which creep ends and true CDW sliding commences. The plot of $v_T^* = f(E=E_T^*) \times \lambda_c$ vs. $1/T$ for pure and Ta-doped crystals in Figure 2 shows that this threshold velocity is temperature activated with an activation energy comparable to Δ_c . The corresponding frequencies $f(E=E_T^*)$ are comparable to estimates of the frequency of thermal activation over local pinning barriers [4].

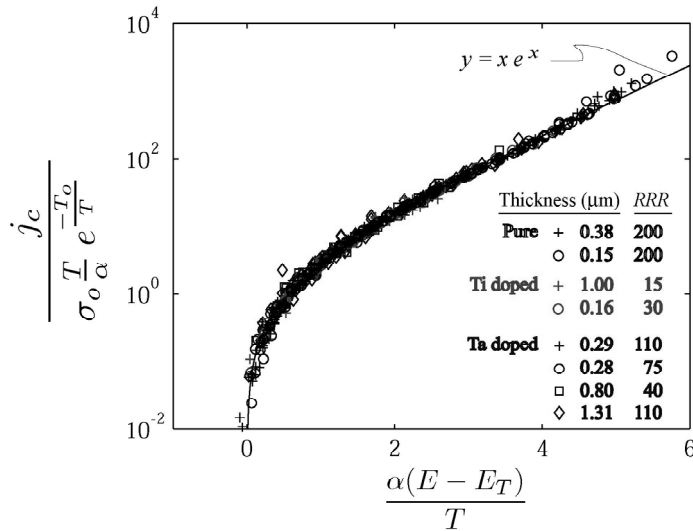


Figure 1: $j_c(E)$ data sets from all studied crystals scaled to fit Equation [1], which can be rewritten in the form $y = x \exp(x)$ where $x = \alpha(E - E_T)/T$.

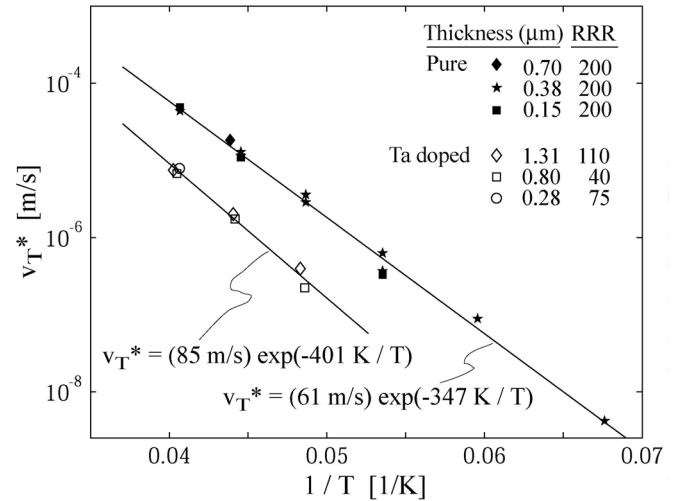


Figure 2: Threshold velocity, $v_T^* = \lambda_c f(E=E_T^*)$, versus inverse temperature for several pure and Ta doped crystals.

References

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