Dynamics of a charge density wave in a quasi-1D conductor with a distribution of threshold fields

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Experimental results on the response of a charge density wave in a quasi-1D $NbSe_3$ conductor to weak microwave radiation in the presence of a microwave pump and a static bias field can be described satisfactorily by a classical model of a overdamped oscillator when the response is averaged with the help of a distribution of threshold fields.

The dynamics of a charge density wave (CDW) in static and alternating fields has been the subject of many studies. Most of the experimental work on the nonlinear dynamic response of a CDW has been carried out on trichalcogenides of transition metals,[1,3] $NbSe_3$ and TaS_3. Most studies have examined the response of the CDW to the application of two alternating signals at frequencies ω and 2ω, with a static bias field (the harmonic-mixer regime). The results of these studies are interpreted on the basis of a tunneling model for the motion of a CDW; the concept of a photon-stimulated tunneling is invoked.[4] The experimental results agree in a quantitatively satisfactory way with results calculated on the basis of this model in the megahertz range.[2] The analysis of the response of a CDW in the harmonic-mixer regime to a microwave signal, which was carried out on the basis of the tunneling model in Ref. 1, does not appear to be correct, since that model ignores the dispersion of the electrical conductivity of CDW in the microwave range.[5] The dispersion of the electrical conductivity of a CDW over a broad frequency range (down to the millimeter range) can be described by the classical model of an overdamped oscillator.[6] The experimental frequency dependence of the electrical conductivity, $\sigma(\omega)$, can be fitted best by the theoretical dependence by introducing a distribution function for the pinning frequency ω_0, which is used as a parameter in the oscillator model, and by averaging $\sigma(\omega)$ over ω_0 (Refs. 7 and 8).

We will apply this idea of averaging $\sigma(\omega)$ to the case of a nonlinear dynamic response of a CDW to the application of microwave radiation. We will use the phenomenological model of an overdamped oscillator.[6] We start with the assumption that each chain in the quasi-1D conductor consists of a sequence of distinct, noninteracting domains of a CDW, each characterized by a distinctive pinning frequency.[8] There is a single-valued relationship between the pinning frequency ω_0 and the threshold field of the domain, $E_{\rm thr}$. We introduce the distribution of the threshold field:

$$P(E_{\rm thr}) = \frac{1}{E^*}\left(\frac{E_{\rm thr}}{E^*}\right)^n e^{-(E_{\rm thr}/E^*)} \qquad (1)$$

where E^* and n are the parameters of the distribution.

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We will use (1) to find the response of the CDW to microwave radiation under conditions such that two microwave signals with approximately equal frequencies ω_1 and ω_2 and with different electric field amplitudes ($E_2 \ll E_1$) are applied to the sample along with a static bias field $E_0 \gg E_2$. The response arises as a current at the difference frequency $\Omega = \omega_2 - \omega_1$, which causes a voltage drop $V_\Omega \cos(\Omega t + \psi)$ across the load resistance in the external circuit.

In formulating the problem we start with the assumption that the CDW responds to the sum of the two signals with the approximately equal frequencies ω_1 and ω_2, with $E_2 \ll E_1$, as if it were a single signal with a slowly varying amplitude[9]:

$$e(t) = e_1 (1 + m \sin \Omega t), \tag{2}$$

where

$$m = e_2 / e_1 \tag{3}$$

satisfies $m \ll 1$, $\omega_1 \approx \omega_2 = \omega$, and e_1 and e_2 are the fields E_1 and E_2 after normalization by division by the threshold field $E_{\rm thr}$. This formulation of the problem corresponds to the experimental conditions of Ref. 10. The equation of motion of the CDW is written as follows on the basis of the model of Ref. 6 with our expression (2):

$$\frac{1}{\omega_0^2} \frac{d^2\theta}{dt^2} + \frac{1}{\omega_{c0}} \frac{d\theta}{dt} + \sin\theta = e_0 + e(t) \, . \tag{4}$$

where θ is the phase of the CDW, $\omega_{c0} = \omega_0^2 \tau$, and τ is a phenomenological damping constant. Under the conditions $m \ll 1$ and $\Omega \ll \omega$, Eq. (4) has the solution

$$\theta = \theta_0 + \theta_m \sin \Omega t .$$

The current of the CDW is determined by the derivative $d\theta/dt$, which must be averaged over the fast variable processes. This problem was solved in Ref. 11 in order to find the response of a CDW, in the form of a current increment $\Delta j_{\rm cdw}$, to the application of a weak continuous microwave signal. Substituting a modulated amplitude of the microwave signal, $e_m = e_1(1 + m \sin \Omega t)$ into the expression for $\Delta j_{\rm CDW}$, and expanding it in a series in the small parameter m, we can extract the variable component of the CDW which varies at the frequency Ω:

$$j_\Omega = \sigma_b E_{\rm thr} \frac{m e_1^2}{2} \frac{1}{\sqrt{e_0^2 - 1}} f(\omega) \sin \Omega t \qquad e_0 > 1, \tag{5}$$

where $f(\omega) = (\omega/\omega_0)^4 [1 + (\omega\tau)^{-2}]$, and σ_b is the conductivity of the CDW which corresponds to the maximum of the Re $\sigma(\omega)$ dependence.

We switch from the current density to the current $i_\Omega = j_\Omega S$ in (5), and we switch from the field to the voltage $V = El$ (l and S are the length and cross-sectional area of the sample). As the current i_Ω flows through load resistance R_L, the total voltage across the sample is $V_\Sigma = V_0 - i_\Omega R_L$. We now substitute V_Σ for V_0 in (5). Solving the resulting equation for the current i_Ω, we find its amplitude

$$I_\Omega = \frac{V_1 V_2}{2V_0} f(\omega)\left(R_L + R_b \frac{\sqrt{V_0^2 - V_{\rm thr}^2}}{V_0}\right)^{-1}, \tag{6}$$

where V_0, V_1, V_2, and $V_{\rm thr}$ are the bias voltage, the voltage amplitudes of the alternating signals, and that of the threshold voltage, respectively; $R_L = R_{\rm ex} R_a/(R_{\rm ex} + R_a)$, where $R_{\rm ex}$ is the resistance of the external load; R_a is the electrical conductivity of the sample which is a consequence of one-particle excitations; and R_b is the resistance determined by the conductivity σ_b.

It follows from (6) that the current I_Ω is determined by a voltage source with an emf $V = (V_1 V_2/2V_0) f(\omega)$ and by the internal resistance $R_i = R_b \sqrt{V_0^2 - V_{\rm thr}^2}/V_0$. The voltage amplitude of the response, $V_\Omega = I_\Omega R_L$, is conveniently written in the following form, where we are making use of (6):

$$V_\Omega = \frac{V_1 V_2}{2V_0} f(\omega)\varphi(E_0, E_{\rm thr}), \tag{7}$$

where

$$\varphi(E_0, E_{\rm thr}) = \begin{cases} 0 & E_0 < E_{\rm thr} \\ \dfrac{\alpha_R E_0}{\alpha_R E_0 + \sqrt{E_0^2 - E_{\rm thr}^2}} & E_0 > E_{\rm thr} \end{cases} \tag{8}$$

$\alpha_R = R_L/R_b$.

Function (8) is discontinuous at $E_0 = E_{\rm thr}$, while the experimental response is a smooth function of E_0. We average response (7) over the set of domains of the CDW, which differ in the value $E_{\rm thr}$, making use of distribution function (1):

$$V_\Omega = \frac{V_1 V_2}{2V^*} f(\omega)\, \varphi(\overline{E_0, E_{\rm thr}}), \tag{9}$$

where

$$\varphi(\overline{E_0, E_{\rm thr}}) = \frac{\alpha_R}{2} \int_0^a \frac{x^n e^{-x}}{\alpha_R a + \sqrt{a^2 - x^2}}\, dx, \tag{10}$$

$x = E_{\rm thr}/E^*$, $a = E_0/E^*$, $V^* = E^* l$.

Let us compare this result with experiment.[10] Figure 1 shows the experimental behavior of the response of the CDW to microwave radiation with a power of 10^{-8} W with a frequency of 3.3 GHz for a $NbSe_3$ sample at $T = 35$ K for various pump power

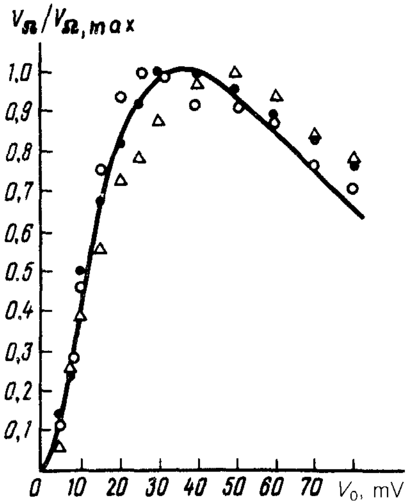

FIG. 1. Normalized voltage amplitude of the response of a CDW to microwave radiation versus the bias voltage. Solid line—theoretical; points—experimental, at various pump levels (microwatts): ○) 40; ●) 110; △) 200. The frequency of the response voltage is $\Omega/2\pi = 36$ MGz.

levels P_{pump}. The amplitude of the response for each level of P_{pump} has been normalized to its maximum value. Shown by a solid line here is theoretical function (9), found through a numerical integration of (10) and normalized to a unit maximum.

For a quantitative estimate of the response, we adopted the experimental value $\alpha_R = 1$ and $f(\omega) = (\omega_{c0}/\omega)^2$, with $\omega_{c0}/2\pi = 0.1$ GHz (Ref. 12). As the adjustable parameters we used $n = 2$ and $V^* = 11$ mV. The measured static breakdown voltage of the sample is $V_{\text{thr}} = 6$ mV. The absolute values of the amplitude of the measured voltage, V_Ω, and of that calculated from expression (9) agree within one order of magnitude.

In summary, the introduction of a statistical distribution of threshold fields has found experimental support. The dynamics of a CDW in the nonlinear regime is described satisfactorily on the basis of a phenomenological model of a classical overdamped oscillator.

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