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Sliding-Mode Conductivity in NbSe$_3$: Observation of a Threshold Electric Field and Conduction Noise

R. M. Fleming and C. C. Grimes
Bell Laboratories, Murray Hill, New Jersey 07974

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Two new effects associated with Fröhlich sliding-mode conductivity have been observed in NbSe$_3$. First, nonlinear resistance is observed only after a well-defined threshold field is reached. Second, electric fields above the threshold result in noise in the potential difference across a current biased specimen. We interpret the threshold field as direct evidence of charge-density wave depinning and the noise as a result of charge-density wave motion.

NbSe$_3$ is characterized by two independent charge-density wave (CDW) transitions, at 144 and 59 K.[1-3] As is characteristic of materials with CDW, large increases in the resistance are observed at temperatures below the two phase transitions.[1] NbSe$_3$ is thus far unique among this class of materials in that the extra resistivity associated with the CDW onset may be suppressed with very modest electric fields.[4] An empirical field-dependent conductivity has been written as[4,5]

$$\sigma(E)=\sigma_a+\sigma_b\exp(-E_0/E). \tag{1}$$

It is reasonable to associate the conductivity gained by the application of the electric field with a current-carrying CDW. The possibility of such a "sliding-mode" CDW was first proposed by Fröhlich[6]; however, recent theoretical considerations indicate that an incommensurate CDW in three dimensions is always pinned at zero field.[7-9] The model of a CDW which may be depinned by an electric field is now supported by both theory[10-12] and experiment.[3,5,13] In particular, it has been shown that the CDW amplitude is unaffected by electric fields which suppress over half of the 59-K resistive anomaly.[3] Recent resistivity measurements suggest that E_0 is a function of sample purity[3,13] and that E_0 varies as the square of the impurity concentration.[13] Microwave absorption[5] below 59 K indicates a local, field-induced phase slip of the CDW.

In this Letter we report the observation of two new effects associated with sliding-mode conductivity in NbSe$_3$. First, sliding-mode conduction only takes place when a well-defined threshold field, E_T, is reached. Second, as the electric field is increased above threshold, an abrupt increase in noise appears in the potential difference across a specimen. For slightly higher fields, discrete frequencies with high harmonic content can be detected in addition to the noise. The first effect requires that Eq. (1) be modified

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to read

$$\sigma(E) = \sigma_a \quad (E < E_T),$$
$$\sigma(E) = \sigma_a + \sigma_b \exp[-E_0/(E - E_T)] \quad (E > E_T). \tag{2}$$

The second effect suggests that as the CDW moves subject to a random pinning potential, noise is generated. The appearance of periodic voltage fluctuations in addition to the broad-band noise is highly unusual and is reminiscent of periodic behavior observed in stressed fluids prior to the onset of turbulence.[14]

The growth of the high-quality ($R_{300\text{ K}}/R_{4.2\text{ K}} \sim 200$) $NbSe_3$ specimens used in this experiment has been discussed elsewhere.[3,15] The whisker-shaped samples were mounted on sapphire substrates using four silver paint contacts. A typical lead geometry is shown in the inset to Fig. 1. The samples were placed in helium-filled capsules where temperature control was maintained by a closed-cycle helium refrigerator. The samples were normally current biased using either a battery or an electronic current supply.

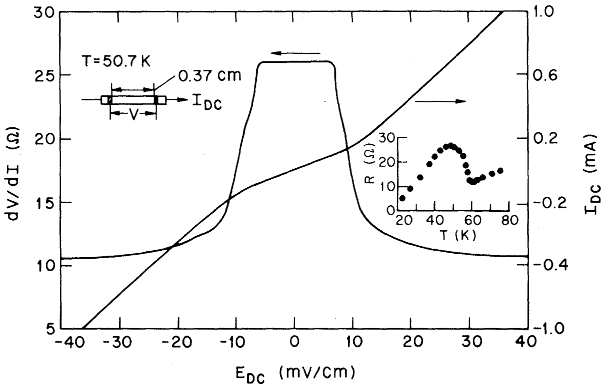

FIG. 1. The presence of a threshold field which signals the onset of nonlinear resistance is indicated by a plot of the dynamic resistance as a function of dc electric field. Also shown is the dc current-field characteristic. The inset is a plot of the temperature dependence of the dc resistance for $E < E_T$.

Both dynamic resistance and noise measurements were made. In the case of dynamic resistance measurements, a small component of ac current was added to the dc bias and the ac component of the resulting voltage was detected with a lock-in amplifier. For noise measurements, only a dc bias was applied to the specimen. A PAR 114 preamplifier with a gain of 500 and low and high 3-dB points at 1 kHz and 1 MHz was used. The amplified signal was detected with either a narrow-band amplifier, a Tektronix 7L5 spectrum analyzer, or a digital transient recorder and multichannel analyzer.

A plot of the dynamic resistance of $NbSe_3$ as a function of dc electric field is shown in Fig. 1. Also shown is a dc I-V curve taken at the same temperature. The data clearly show Ohmic behavior at fields below about 5 mV/cm. From Eq. (2) one may derive an expression for dV/dI, given that $\vec{J} = \sigma\vec{E}$:

$$\frac{dV}{dI} = R_0 \quad (E < E_T); \quad \frac{dV}{dI} = R_0\left[1 + \frac{\sigma_b}{\sigma_a}\left(1 + \frac{EE_0}{(E - E_T)^2}\right)\exp\left(\frac{-E_0}{E - E_T}\right)\right]^{-1} \quad (E > E_T). \tag{3}$$

R_0 is the sample resistance below the threshold field. Equation (3) was least-squares fitted to the data shown in Fig. 1 with $\sigma_b/\sigma_a = 1.37$, $E_0 = 15.8$ mV/cm, and $E_T = 4.4$ mV/cm. The fit is very good and clearly indicates the presence of a threshold electric field for non-Ohmic conduction as well as the validity of the exponential falloff of the nonlinear conductivity. We found E_T to be temperature dependent with a minimum value near the resistance maximum ($T \approx 48$ K). E_T diverges sharply as T approaches T_c from below. Preliminary data indicate that E_T is also impurity dependent. A second sample with $R_{300\text{ K}}/R_{4.2\text{ K}} = 37$ was fitted by Eq. (3) with the following parameters at $T = 50.1$ K: $\sigma_b/\sigma_a = 1.24$, $E_0 = 132$ mV/cm, and $E_T = 31.7$ mV/cm.

We now turn to noise measurements in $NbSe_3$. For a depinned CDW, one might expect that the motion of the CDW through an array of pinning sites would result in conduction noise. To investigate this possibility, the ac portion of the dc bias was removed. The signal was detected with a lock-in amplifier used in an ac voltmeter mode with a bandpass prefilter. This resulted in a narrow-band amplification of the signal with $Q = 12.34$. Figure 2 shows the rectified amplifier output as a function of dc current for frequencies in the interval 10–100 kHz. For currents below threshold, the noise output is primarily instrumental. At currents corresponding to E_T, an abrupt broad-band increase in noise occurs. At higher currents, discrete frequencies appear as evidenced by the sharp structure in the amplifier output. Differences in the signal between positive and negative current are attributed to differences

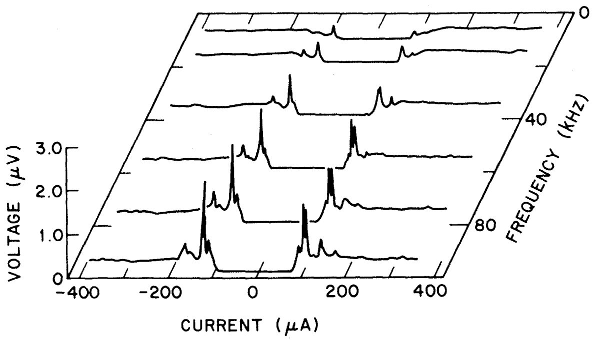

FIG. 2. Output of a lock-in amplifier used in an ac voltmeter mode at selected values of a bandpass prefilter. At currents corresponding to E_T, an abrupt increase in noise is observed. Structure in lock-in output indicates presence of discrete frequencies. $T = 47.7$ K.

in $+\vec{j}$ and $-\vec{j}$ due to imperfect current contacts.

A spectral analysis of the noise output was made using an on-line spectrum analyzer with the dc current held at a number of constant values. Figure 3 shows the intensity of the signal [after preamplification of 27 dB(V)] as a function of frequency for a number of different currents. The amplitude of the signal above 1 MHz is not reliable because of finite amplifier bandwidth. As the current is increased from zero [Fig. 3(e)] to a value above threshold [Fig. 3(d)], the broad-band noise increases by about a factor of 10. In addition to broad-band noise, a well-defined frequency and many harmonics are present. The fundamental frequency is slightly broader than instrumental resolution with a full width at half maximum of 5 kHz at 200 kHz. At higher values of current, additional frequencies and their harmonics can be detected. All frequency components initially appear at frequencies near zero in magnitude with $df/dI \approx 0$. At higher values of current, all frequencies increase approximately linearly with current. For the current range studied, two frequencies are dominant. A weak third frequency may be detected in Figs. 3(a) and 3(b); however, it is much broader with no observed harmonics. The frequencies were not tracked above 2 MHz because of limitations imposed by the preamplifier bandwidth. It should be emphasized that the observation of these frequencies is clearly associated with the nonlinear conductivity. No excess noise of periodic voltage fluctuations are observed at fields below E_T or temperatures above T_c.

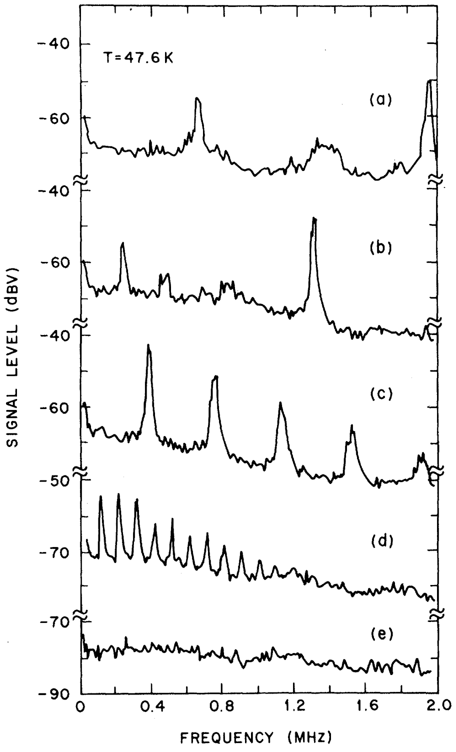

FIG. 3. Output of on-line spectrum analyzer for selected values of current. Increasing current from zero (e) to a value above threshold (d) results in an increase of broad-band noise plus a discrete frequency with numerous harmonics. The frequency increases with current and at higher currents (b) a second frequency appears. Currents and dc voltages (a) $I = 270$ μA, $V = 5.81$ mV, (b) $I = 219$ μA, $V = 5.05$ mV, (c) $I = 154$ μA, $V = 4.07$ mV, (d) $I = 123$ μA, $V = 3.40$ mV, (e) $I = V = 0$. Sample cross section ≈ 136 μm^2.

The observation of a threshold field coupled with a noise output strongly reinforces the model of sliding-mode conductivity in $NbSe_3$. Early resistance measurements[4,5] indicated that the field-dependent conductivity is given by Eq. (1). A similar expression is obtained in theories of Maki[11] and Bardeen[12] which are based on Zener-type tunneling. The observation of a threshold field and a conductivity given by Eq. (2) is more consistent with the breakway conduction process described by Lee and Rice[10] where the entire CDW moves.

Qualitatively, the observation of noise is explained by motion of the CDW. The most unusual aspect of the data is the appearance of periodic voltage fluctuations. The fluctuating voltage has been studied in real time by summing repetitive measurements of the signal and then looking at only the periodic portion of the voltage. These measurements show that the fundamental frequency is coherent for 30–50 cycles. The wave form rapidly evolves from a series of voltage spikes to sine wave in shape indicating that the phase coherence of the high harmonics is not nearly so long. This last result is not unexpected if one has coupling of the periodic signal to the broad-band noise. A more puzzling feature is the extremely low value of the periodic frequencies. The mobility of the carriers has been estimated[16] to be about 3000 cm^2/V s at 50 K. If one makes the assumption that the CDW drift velocity is roughly the same as that of the normal carriers, the low frequencies imply a characteristic length ~1 μm. This length appears to be much longer than any relevant length in the problem such as the CDW wavelength. The low frequencies may suggest a macroscopic effect involving a coupling to another material property such as the electronic heat capacity. One effect of this type is the Gunn effect where oscillations result from electron promotion to a low-mobility subband and a resulting negative differential resistance.[17] Such a process does not appear to be occurring in $NbSe_3$ because the measured differential resistance is always positive and the resistance decreases with current.

An intriguing analogy involves a comparison of the noise data to the onset of turbulence in hydrodynamics. In a variety of fluid systems[14] the transition from laminar to chaotic flow is accompanied by intermediate periodic and quasiperiodic regimes. Qualitatively this behavior is similar to the effects seen in $NbSe_3$; however, there are several differences. In fluid systems the frequencies appear at finite values and depend only mildly upon the Reynolds number. The frequencies in the fluid case are always instrumentally narrow, but the finite bandwidths in $NbSe_3$ may result from coupling to the concurrent broad-band noise. To carry this analogy further, one needs to show that conduction in $NbSe_3$ can be expressed by coupled nonlinear equations. It will be interesting to see if further theoretical studies can relate these two phenomena.

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