Field-Effect Modulation of Charge-Density-Wave Transport in $NbSe_3$ and TaS_3

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We have constructed MOSFET-like structures using the quasi-one-dimensional conductors $NbSe_3$ and TaS_3. At temperatures below the Peierls transition, an applied gate voltage modulates the threshold field for sliding motion of charge-density waves by up to 40%. The resulting modulation of the collective conductance can be more than 2 orders of magnitude larger than that of the single-particle conductance. We consider several possible mechanisms for this conductance modulation, and suggest electric-field-induced variations of the charge-density-wave order parameter as the most plausible mechanism.

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In field-effect devices, a capacitor is formed using two dissimilar conducting materials as plates [1]. When a voltage is applied between the plates (the "gate" and "channel"), charge accumulates in the channel to screen the electric field, modulating the channel conductivity. The field effect has broad applications as a probe of transport and interface properties, and in electronic devices such as MOSFETs. Here we describe a field-effect device in which the channel is formed by a charge-density-wave (CDW) conductor. We observe a large modulation of the collective charge transport due to CDW motion, and discuss possible novel mechanisms for field-effect conduction modulation.

Charge-density waves form below Peierls transitions in a variety of quasi-one-dimensional metals, producing an energy gap 2Δ at the Fermi surface [2]. A CDW consists of a lattice distortion coupled to an electron density modulation $n(x) = n_c + n_1 \cos[Qx + \phi(x,t)]$, where $Q = 2k_F$ and ϕ is the phase of the CDW order parameter. For small applied electric fields, the CDW remains pinned to defects of the underlying lattice and only a single-particle current i_s flows. Above a threshold field E_T, the CDW can depin from defects and slide through the crystal, providing a collective current i_c which adds to i_s [3].

$NbSe_3$, the most widely studied CDW material, forms two independent CDWs [4]. The first forms at $T_{P_1} = 145$ K, and removes roughly half the total metallic carrier density $n_s = 3.8 \times 10^{21}$ cm^{-3} [5–7]. The second forms at $T_{P_2} = 59$ K, leaving a small part of the Fermi surface with $n_s \approx 6 \times 10^{18}$ cm^{-3} ungapped, so that the low-field conduction remains metallic down to low temperatures.

To fabricate the CDW field-effect devices, a 550 Å SiO_2 film was thermally grown onto a degenerately doped Si wafer. A thin, freshly cleaved $NbSe_3$ crystal was then placed on the oxide, and electrical contacts formed by pressing 50 μm indium wires to the crystal. Contact separations were $L \approx 100$–800 μm, and crystal cross-sectional areas A were 10^{-3}–10^{-1} μm^2.

Conduction by the $NbSe_3$ channel was measured as a function of gate voltage V_G at temperatures between 300 and 20 K [8]. The gate voltage is applied between the silicon substrate and one of the two channel contacts; for positive V_G, the gate potential relative to the channel is positive and induces a negative channel charge. Leakage currents through the oxide were too small to be measured, and oxide breakdown voltages were in excess of 30 V. In most cases, the gate voltage was much larger than the voltage drop along the $NbSe_3$ channel (typically 0.1–1 V) [9]. Since the total carrier density in $NbSe_3$ is large, very thin crystals (thicknesses $t \ll 1$ μm) were used in order that gate-voltage-induced charges be an appreciable fraction of the total.

Figure 1 shows the I-V characteristic of a very thin $NbSe_3$ channel at $T = 30$ K for several gate voltages. The linear response at low fields is due to single-particle current i_s, and has a gate-voltage variation that is too small to be visible in Fig. 1. In contrast, the collective response is strongly modulated. When the CDW is biased near the depinning threshold, V_G variations can turn CDW

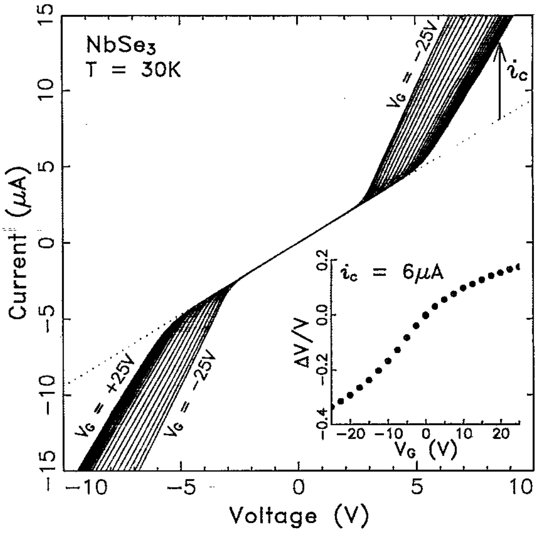

FIG. 1. Current-voltage characteristics of a 1.1×10^{-3} μm^2 $NbSe_3$ crystal at $T = 30$ K, for gate voltages V_G from −25 to 25 V in 2.5 V increments. The gate voltage produces a large modulation of the threshold field for CDW conduction, E_T, but has little effect below threshold. The inset shows $[V(V_G, i_c) - V(0, i_c)]/V(0, i_c)$ at $i_c = 6$ μA, used as an estimate of $[E_T(V_G) - E_T(0)]/E_T(0)$.

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conduction on and off. The curves for different V_G are nearly parallel above threshold, and the dominant effect is a modulation of the threshold E_T [10].

The inset to Fig. 1 shows the fractional voltage modulation $[V(V_G, i_c) - V(0, i_c)]/V(0, i_c) \approx [E_T(V_G) - E_T(0)]/E_T(0)$ vs V_G for $i_c = 6\ \mu\text{A}$. The voltage modulation is proportional to V_G for small V_G, and is positive for positive V_G. All samples studied showed voltage modulations with the same sign, and the sample shown had the largest fractional modulation. Systematic variation of the modulation magnitude with sample cross-sectional area has not been determined.

Figure 2 shows the sensitivity of the CDW to gate voltage variations $\alpha_c \equiv (1/V)\partial V/\partial V_G$, at fixed i_c, versus temperature for the low-temperature ($T_{P_2} = 59$ K) CDW in NbSe_3. The sensitivity increases with decreasing temperature down to $T = 28$ K, and then decreases at lower temperatures.

Figure 3 shows the fractional modulation of the single-particle resistance $\delta R_s/R_s$ versus gate voltage V_G for NbSe_3. The single-particle resistance varies linearly with gate voltage over the entire temperature range studied. Figure 4 shows the sensitivity $\alpha_s \equiv (1/R_s)dR_s/dV_G$ versus temperature. α_s for NbSe_3 has two peaks which occur slightly below T_{P_1} and T_{P_2}, respectively, the latter being much larger and sharper. α_s changes sign below the low-temperature peak and is hysteretic below 20 K.

To analyze these results, we first consider the behavior above the $T_{P_1} = 145$ K Peierls transition, where NbSe_3 is metallic. A voltage applied to the gate-channel capacitor induces a charge which screens the transverse electric field. The resulting fractional change in channel carrier density should produce a corresponding fractional change in channel conductivity, so that

$$\alpha_s \equiv \frac{1}{R_s}\frac{\partial R_s}{\partial V_G} \approx \frac{\epsilon\epsilon_0}{q n_s t d}, \qquad (1)$$

where ϵ and d are the dielectric constant and thickness of the dielectric layer, q is the charge of the current carriers, t is the sample thickness, and n_s is the single-particle density. Figure 5 shows the measured sensitivity α_s at $T = 300$ K versus the cross-sectional area A of the NbSe_3 channel. The dashed line is the prediction of Eq. (1) using $\epsilon = 3.85$ and $t = \sqrt{A}$. The measured magnitude agrees well with the prediction of Eq. (1) [11] and the sign indicates hole-type conduction, consistent with Hall measurements [6]. The quantitative agreement suggests that interface states are not important in these devices, perhaps as a consequence of NbSe_3's quasi-one-dimensional character. For a gate voltage of 15 V and a channel cross-sectional area of $10^{-3}\ \mu\text{m}^2$, the induced charge is roughly 0.1% of the total channel carrier density. This charge should screen the transverse electric field in roughly a Thomas-Fermi length, which is on the order of 10 Å.

Below the Peierls transitions, both the single particles and the CDW screen the transverse field. The total screening charge depends only upon V_G and is independent of temperature. Between T_{P_2} and 20 K, the single-particle density in NbSe_3 decreases by more than 3 orders of magnitude. But, as shown in Fig. 4, the single-particle sensitivity α_s has a much smaller temperature variation. Consequently, at low temperatures nearly all of the screening is performed by the CDW.

Figure 5 suggests that gate-voltage-induced changes in single-particle density produce a proportionate fractional change in single-particle conductivity. If this were also true for the CDW charge and conductivity, then the sensitivity α_c below the Peierls transition would be comparable to α_s in the metallic state above $T_{P_1} = 145$ K.

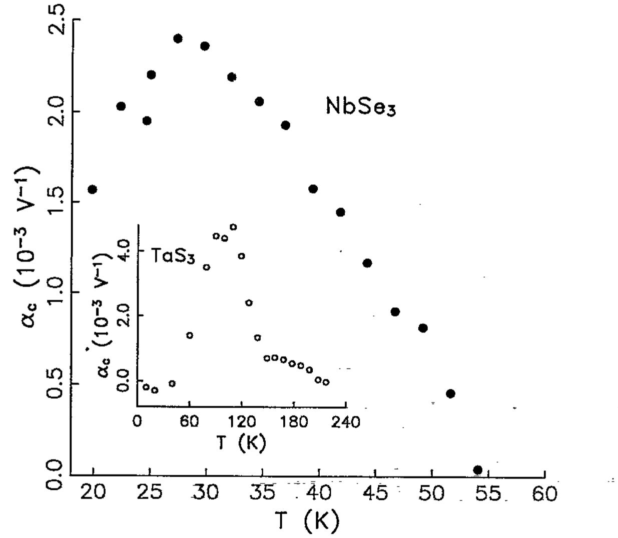

FIG. 2. Gate-voltage sensitivity $\alpha_c \equiv (1/V)\partial V/\partial V_G$ in the sliding CDW state above threshold vs temperature at $i_c = 6\ \mu\text{A}$, for a $5.7 \times 10^{-3}\ \mu\text{m}^2$ NbSe_3 crystal. The inset shows $\alpha_c(T)$ for a $5 \times 10^{-3}\ \mu\text{m}^2$ TaS_3 crystal.

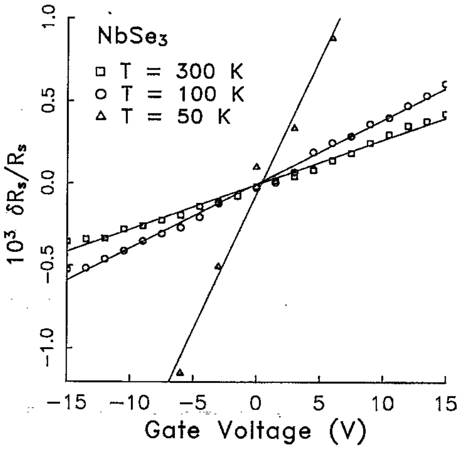

FIG. 3. Fractional variation of the single-particle resistance R_s with gate voltage V_G for a $5.7 \times 10^{-3}\ \mu\text{m}^2$ NbSe_3 sample at $T = 300$ K (in the metallic state), 100 K (where the first CDW has formed), and 50 K (where both CDWs have formed). At all temperatures, the variation is approximately linear.

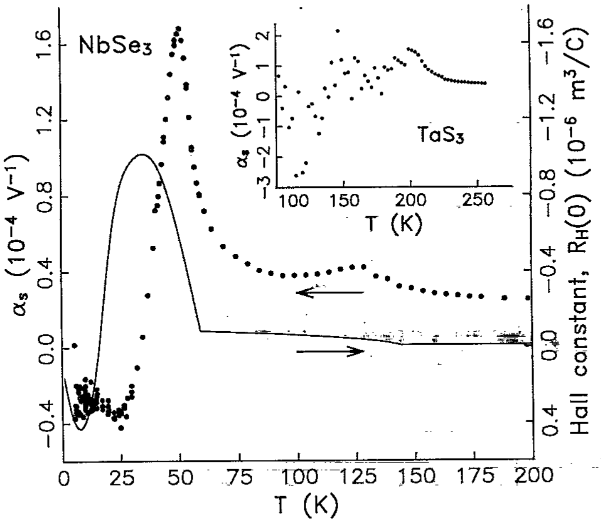

FIG. 4. Gate-voltage sensitivity $\alpha_s \equiv (1/R_s)\partial R_s/\partial V_G$ of the single-particle resistance R_s vs temperature for a 5.7×10^{-3} μm^2 NbSe$_3$ crystal. The temperature variation of the Hall constant $R_H(0)$ [6] is shown for comparison. The inset shows $\alpha_s(T)$ for a 5×10^{-3} μm^2 TaS$_3$ crystal.

As shown in Figs. 1, 2, and 4, α_c is, in fact, more than 3 orders of magnitude larger than α_s in the metallic state. How do relatively small changes in CDW charge density (less than 0.1%) produce such large changes (up to 100%) in the CDW conductivity? There are several possibilities.

First, to screen the transverse field, the CDW must develop a transverse variation in charge density. Since the CDW charge density $n_c \propto k_F \propto Q$, this requires a transverse variation in CDW wavelength which most likely involves formation of CDW dislocations [12]. Dislocations could modify CDW conduction by providing additional pinning, by facilitating depinning of more weakly pinned regions from more strongly pinned regions (e.g., near the crystal surface), or by facilitating the phase slip required for current conversion at the current contacts. In each case, the effect on CDW conduction should be proportional to the dislocation density, and should thus have *even* symmetry with respect to V_G. As shown in Fig. 1, the observed symmetry is *odd*.

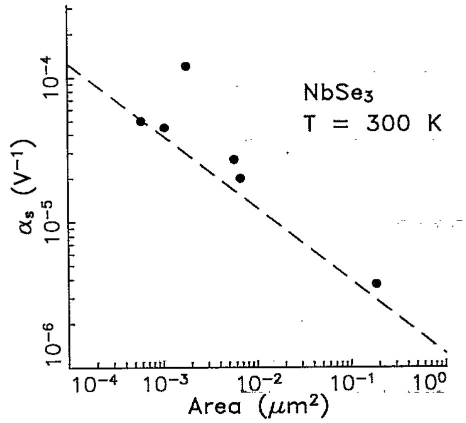

FIG. 5. Single-particle gate-voltage sensitivity α_s vs crystal cross-sectional area. The dashed line indicates the prediction of Eq. (1) with $t = \sqrt{A}$.

Second, gate-voltage-induced CDW charge-density variations could modify CDW pinning by driving the CDW wave vector towards commensurability with the underlying lattice. For the T_{P_2} CDW in NbSe$_3$, the wave vector $Q = 0.259$ is roughly 3% larger than the commensurate value $Q = 0.250$. A 3% change in wave vector would require a 3% change in n_c. This is much larger than the estimated 0.1% change in total charge density at large gate voltages in Fig. 1.

Third, gate-voltage-induced variations in CDW charge density near the crystal surface could change the charge modulation amplitude n_1 there and thus change the strength of CDW pinning by the surface nearest the gate. However, there is no clear evidence for the importance of surface pinning in determining E_T in NbSe$_3$.

A fourth possibility is that the large CDW conduction modulation is due to changes in CDW pinning arising from gate-voltage-induced variations in the CDW energy gap 2Δ. The depinning threshold field E_T in the weak-pinning limit can be expressed as [13]

$$E_T \propto \Delta^{4/(4-d)}/K^{4/(4-d)-1}, \tag{2}$$

where K is the CDW elastic constant and d is the dimensionality of the pinning. The sensitivity α_c is thus given approximately by

$$\alpha_c \approx \frac{1}{E_T}\frac{dE_T}{dV_G} = \left[\left(\frac{4}{4-d}\right)\frac{1}{\Delta} - \left(\frac{4}{4-d} - 1\right)\frac{1}{K}\frac{dK}{d\Delta}\right]\frac{d\Delta}{dV_G}. \tag{3}$$

For NbSe$_3$, $dK/d\Delta \approx 0$ at temperatures well below T_P [14] so that α_c should have the same sign as $d\Delta/dV_G$. The sign of $d\Delta/dV_G$ can be determined from Fig. 4. An increase in Δ due to V_G will increase $T_P \propto \Delta$. Since the single-particle resistance for NbSe$_3$ increases below T_P, an increase in T_P will increase the resistance at fixed T near T_P. In Fig. 4, the peaks in α_s just below the Peierls transitions correspond to an increase in R with increasing V_G. Thus, $d\Delta/dV_G$ is positive, in agreement with the measured value $\alpha_c > 0$.

The magnitude of the gate-voltage-induced gap modulation deduced using Eq. (2) from Fig. 1 for $V_G = 15$ V is roughly 10% [15]. Since the estimated carrier density modulation is only 0.1%, this gap modulation seems extremely large. However, we note that in experiments on the CDW conductor K$_{0.3}$MoO$_3$ changes in volume due to applied hydrostatic pressures which produced comparable carrier density changes to those obtained here were found to yield comparable variations in the CDW gap [16].

For the gate voltage to affect CDW pinning as described above, the transverse electric field must penetrate a significant distance into the $NbSe_3$ channel. The penetration depth d_p will depend upon the competition between the electric-field energy U_E and the dislocation energy U_D. The electric field is proportional to V_G so that $U_E \propto V_G^2 d_p$. The total charge to be screened is proportional to V_G; the excess charge per unit area is proportional to the dislocation density; and the charge associated with an edge dislocation is proportional to its penetration depth d_p into the channel. Since the dislocation energy is proportional to the total number of dislocations N_D, $U_D \propto N_D \propto V_G/d_p$. Minimizing the total energy yields $d_p \propto V_g^{-1/2}$. Thus, for small gate voltages U_D dominates and the dislocations and electric field will penetrate far into the channel. For large voltages U_E dominates, and they will be concentrated near the surface.

We have also fabricated field-effect devices using the CDW conductor TaS_3. TaS_3 differs from $NbSe_3$ in that it undergoes a single Peierls transition at $T_P = 220$ K which gaps the entire Fermi surface, so that its single-particle conduction becomes semiconducting [3]. As in $NbSe_3$, both the CDW and single-particle conduction are modulated by an applied gate voltage. The temperature-dependent sensitivities α_c and α_s are shown in Figs. 2 and 4 and have magnitudes comparable to those in $NbSe_3$ [17,18].

In conclusion, we have demonstrated field-effect modulation of both single-particle and collective transport in the charge-density-wave conductors $NbSe_3$ and TaS_3. Several modulation mechanisms have been considered, of which field-induced variations of the CDW gap appear the most promising. However, none of these mechanisms can easily account for the large magnitude of the collective conductance modulations.

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[8] Channel *I-V* measurements performed using two- and four-contact methods gave identical results, as expected for our thin samples. All of the data in Figs. 1–5 were acquired using two contacts.

[9] Channel voltages of up to 10 V were required to depin the CDW in the thinnest $NbSe_3$ crystal, and of up to 20 V to depin the CDW in TaS_3 at low temperatures.

[10] For the sample of Fig. 1, the CDW threshold voltage measured between the channel contacts is comparable to V_G, so that the gate-channel voltage varies appreciably along the channel. This results in a small leftward shift of the *I-V* curves in Fig. 1 for large channel voltages.

[11] Using $t = \sqrt{A}$ in Eq. (1) underestimates α_s since the thickness of $NbSe_3$ crystals is generally less than their width.

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[15] This assumes $d = 2$ in Eq. (3), appropriate for the very thin crystals used here. See J. P. McCarten *et al.,* Phys. Rev. B **46**, 4456 (1992).

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[17] In the metallic state above T_P, the sign of α_s agrees with the sign of the Hall coefficient (Yu. I. Latishev, Ya. S. Savitskaya, and V. V. Frolov, Pis'ma Zh. Eksp. Teor. Fiz. **38**, 446 (1983) [Sov. Phys. JETP Lett. **38**, 541 (1983)]) and implies that conduction is by holes. Using $n_s = 1.5 \times 10^{21}$ cm^{-3}, $d = 550$ Å, and $t = \sqrt{A}$ with $A = 5 \times 10^{-2}$ μm^2, appropriate for the sample of Fig. 4, Eq. (1) gives $\alpha_s = 1.3 \times 10^{-5}$ 1/V, close to the observed value of 4×10^{-5} 1/V.

[18] The large scatter in α_s below T_P in TaS_3 is likely due to CDW metastability. Single-particle conduction in this case is only by thermally excited electrons and holes, whose balance is very sensitive to metastable changes in the pinned CDW configuration. These metastable changes produce a large temperature-dependent hysteresis in the $V_G = 0$ V single-particle conductivity (e.g., up to 40% at $T = 100$ K).