Tunable Charge Density Wave Transport in a Current-Effect Transistor

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The charge-density-wave (CDW) state, characterized by a periodic modulation of the conduction electron density, is commonly observed in low-dimensional conductors [1]. It is found to be the ground state in various inorganic and organic materials with a chain-like structure, giving rise to remarkable electrical properties [2,3]. Similar charge-ordered states (“striped phases”) play an important role in high-Tc superconductors [4] and two-dimensional electron gases in the quantum Hall regime [5].

A particularly interesting feature of the CDW state is its collective transport mode, very similar to superconductivity [6]. Under an applied electric field, the CDWs slide along the crystal, giving rise to a strongly nonlinear conductivity. Since even a small amount of disorder pins the CDWs, sliding occurs only when the applied electric field exceeds a certain threshold field. The pinning mechanisms, the onset of collective motion and the dynamics of a moving CDW are typical characteristics of the complex physics which describes a very general class of disordered periodic media [6,7]. These include a wide variety of periodic systems, as diverse as vortex lattices in superconductors and Josephson junction arrays [6,8], Wigner crystals [9], colloids [10], magnetic bubble arrays [11], and models of mechanical friction [12].

The focus of recent theoretical and experimental research on disordered periodic media have been their nonequilibrium dynamical properties. One of the issues that have been raised is the effect of a single-particle current, due to uncondensed electrons and quasiparticle excitations. In a recent theoretical work, Radzihovsky and Toner [12] discovered that a single-particle current has the most profound effects when it flows perpendicular to the CDW sliding direction. Based on general symmetry principles, this leads to nonequilibrium CDW dynamics even if CDW itself is stationary. Here we report our study of the CDW transport in the presence of such a transverse single-particle current. We find that the sliding CDW motion is stable against a small transverse current, but large currents have a dramatic effect: the longitudinal depinning threshold field is exponentially reduced for the normal current densities which exceed some crossover value \( J_\text{c} \). In other words, the collective longitudinal current is enhanced by the transverse single-particle current. The characteristics of this current-effect transistor are in excellent agreement with the predictions of Radzihovsky and Toner [12].

The experiments were carried out on single crystals of NbSe\(_3\). This material has a very anisotropic, chain-like structure [2]. It exhibits two CDW transitions, each involving different types of chains, at \( T_P = 145K \) and \( T_P = 59K \). A small portion of the conduction electrons remains uncondensed, providing a metallic single-particle channel.

A single crystal of dimensions 2.7 mm \( \times \) 36 \( \mu \)m \( \times \) 240 nm was glued onto a sapphire substrate. A pattern of gold contacts was then defined on top of it using electron-beam lithography. The pattern consisted of two current leads at two ends of the crystal, and a row of devices, each with two transverse current leads and two voltage leads. A scheme of such a transistor device is shown in the inset of Fig. 1.

The transverse current leads were 5-100 \( \mu \)m wide, and overlapped the crystal by 1-5 \( \mu \)m. To ensure contact on both sides of the crystal, 180 nm thick layer of gold was evaporated at angles of 45 degrees with respect to the substrate, as well as perpendicular to it. The contact resistance of the transverse leads was by 1-2 orders of magnitude larger than the resistance of the crystal in the longitudinal direction, which precludes considerable shunting of the current through the transverse leads. A dc current of up to 1 mA was injected at the transverse leads. The transverse leads were not electrically connected to the longitudinal circuit, except through the crystal. Since the CDWs can only slide in the longitudinal direction, the transverse current is due to single electrons.

The longitudinal current was injected at the two far ends of the crystal. The voltage leads were 180 nm thick, 5 \( \mu \)m wide and the spacing between them was 50-500 \( \mu \)m. The longitudinal current-voltage characteristics and the differential resistance were studied as a function of trans-
verse current at different temperatures, ranging from 25-
120 K.

The current-voltage characteristics for one of the de-
vices are shown on Fig. 1. In the absence of the trans-
verse current, the CDWs are pinned at low bias voltages.
The I-V curve is linear, as the current is due to un-
condensed electrons and quasiparticles that are thermally excited
above the CDW gap. When the applied voltage reaches the
threshold value \( V_T(I_x = 0) \), marked by an arrow in
Fig. 1, the CDWs are depinned and start to slide. A
sharp increase in current is observed at \( V_T \) due to this
additional conduction channel.

When a transverse current \( I_x \) is applied, \( V_T \) decreases
and the sliding starts at lower bias voltages. Thus, CDWs
that were pinned for \( J_x = 0 \), start sliding at lower fields
when a transverse current is applied. A new linear regime
sets in at low bias voltages, where \( V_T < V_T(I_x = 0) \).
The resistance in this regime is lower than the single
particle contribution \( R \) at \( J_x = 0 \). This makes the ef-
effort easily distinguishable from heating: since most of
the measurements were carried out at the temperatures
at which \( dR/dT > 0 \), heating would result in a higher
single-particle resistance.

The threshold field reduction is more strikingly visible
in the differential resistance measurements, shown in Fig.
2. The differential resistance at low bias fields, due to un-
condensed electrons and excited quasiparticles, is mostly
unaffected by the transverse current. The onset of CDW
sliding, characterized by a sharp drop in differential re-
sistance, is shifted towards zero as \( I_x \) is increased.
The same reduction of the threshold field is also observed for
negative bias voltages and the plots are nearly symmet-
ric around \( V = 0 \). We have found no differences when
changing the sign of either the longitudinal current or the
transverse current.

The reduction of the sliding threshold does not occur for
arbitrarily small transverse currents. The dependence of the
threshold field \( E_T \) on the transverse current density \( J_x \) for two samples [27] is shown in Fig. 2. It is ev-
ident that \( E_T \) remains unchanged until \( J_x \) reaches some
crossover value \( J_c \). For \( J_x > J_c \), \( E_T \) decreases with in-
creasing \( J_x \). The transverse current density dependence of the
threshold field \( E_T \) for \( J_x > J_c \) can be fit by:

\[
E_T(J_x) = E_T(0) \frac{J_x}{J_c} \exp \left( 1 - \frac{J_x}{J_c} \right) \quad (1)
\]

where \( E_T(0) \) is the threshold field at \( J_x = 0 \). Once
the crossover value of the transverse current \( J_c \) is ex-
ceeded, the depinning threshold field decreases and the
CDW conduction channel is activated by much lower bias
voltages.

The observation of a crossover current \( J_c \) rules out the
possibility that the threshold field reduction is due to
current inhomogeneities around the transverse contacts.
If the changes in \( E_T \) were due to a longitudinal com-
ponent of an inhomogeneous transverse current, then such
changes would be apparent at any value of \( J_x \), and no \( J_c \)
would be observed. Furthermore, it is not clear that such
inhomogeneities would lead to the observed exponential
reduction of \( E_T \).

The exponential decrease of the threshold field de-
scribed by Eq. 1 has recently been predicted by Radz-
ihilovsky and Toner [28]. In their model, the value of
the crossover current density \( J_c \) needed for the initial sup-
pression of \( E_T \) is expected to be proportional to the value of
the threshold field at \( J_x = 0 \), and is given by [26]:

\[
J_c \propto \frac{\sigma_0 E_T(0)}{\xi L k_F} \left( \frac{\rho_n}{\rho_{CDW}} \right) \quad (2)
\]

where \( \sigma_0 \) is the conductivity at very high bias fields, \( k_F \)
the Fermi wave vector and \( \rho_n \) and \( \rho_{CDW} \) are normal and
CDW electron densities, respectively. The correlation
length \( \xi_L \) is a measure for the coherence in the
sample and decreases with increasing disorder.

\( E_T \) is known to be temperature dependent, following
\( E_T = E_T(0) e^{-T/T_0} \). The dependence of \( J_c \) on \( E_T(0) \)
can therefore be studied by measuring at different tem-
peratures. The dependence of \( J_c \) on \( \sigma_0 E_T(0) \) is shown in
the inset of Fig. 3, \( J_c \) grows linearly with \( \sigma_0 E_T(0) \) and
it extrapolates to zero for \( E_T(0) = 0 \). The crossover
current densities of \( 10^3 \text{--} 10^4 \text{A/cm}^2 \) estimated from Eq. 3
[26] are in excellent agreement with the values measured in
our experiment.

We have shown that the conduction in the CDW chan-
nel can be enhanced by a single-particle current flowing
transversely to the CDW sliding direction. This surpris-
ing behavior has been observed in samples with different
geometries, at different temperatures, and in both CDW
regimes of NbSe₃, suggesting that it is a general property of
the CDW transport.

The dynamical model of Radzihovsky and Toner [24]
provides a physical origin of this effect: the CDWs
become more ordered due to momentum transfer with
transversely moving normal carriers. This mechanism is
illustrated in Fig. 4. In the absence of defects, the charge
density wave fronts are straight and parallel to each other
(left side of the picture). The single-particle transverse
current, marked by “a” on Fig. 4, can flow with little
or no interaction with the CDW. In the presence of de-
fects or impurities in the crystal, the CDW deforms to
lower its energy and the wavefronts are “wrinkled” (right
side of the picture). In this case, the transversely mov-
ing electrons (“b”) are more likely to be deflected. The
conservation of linear momentum results in a reaction
force back on the CDW. This way the CDW roughness
is reduced as the CDW wavefronts are straightened out
or “ironed” by the transverse current. The CDW trans-
port across the sample is therefore more coherent and
less susceptible to pinning. The lower pinning strength
then leads to a lower threshold field.

Since the conduction in the CDW channel can be mod-
ulated by a current in the single particle channel, this de-
vice in principle works as a transistor, raising a question of
a possible practical application. The maximum gain
observed in our experiments was $\Delta I/I_x = 0.15$. A simple estimate from our measurements suggests that the maximum gain is proportional to $\xi^{-1}_L$. The gain can therefore be improved by using dirtier crystals or smaller samples in which $\xi_L$ is limited by the sample sizes.

Apart from being intriguing in their own right as an important test of the theory, our results may provide a useful insight into related phenomena which are much more difficult to study experimentally. As mentioned above, this novel effect is relevant to a variety of other periodic systems which share the same symmetries and a similar geometry. A particularly interesting example might be the "striped phases" in superconducting oxides, whose role in high-$T_c$ superconductivity is still not resolved.

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FIG. 1. Current-voltage characteristics for a 36 $\mu$m wide and 0.24 $\mu$m thick NbSe$_3$ crystal at 45 K with the values of the transverse current ranging from 0 (bottom) up to 800 $\mu$A (top). The width of the transverse current leads was 100 $\mu$m, and the spacing between the voltage leads was 225 $\mu$m. The dotted line represents the Ohmic behavior of the uncondensed electrons. The data deviate from that line when the charge density waves are depinned and start to slide, contributing additional current. The depinning threshold $V_T$, marked by an arrow, decreases when a transverse current $I_x$ is applied. Inset: The scheme of the transistor-like device, which consists of the crystal (dark shaded area) and six gold leads (light shaded areas): I for the longitudinal current, which is injected at the far ends of the crystal, $V$ for voltage measurements and $I_x$ for the transverse current injection.

FIG. 2. Differential resistance as a function of electric field at 45 K of the same device as in Fig. 1. Different symbols represent different values of the transverse current $I_x$, ranging from 0 (filled circles) to 190$\mu$A (filled squares). The threshold field at which the differential resistance drops due to the depinning of the charge density waves is shifted to lower values as the transverse current is increased.
FIG. 3. Depinning threshold field $E_T$, scaled by its value at $J_x=0$, as a function of transverse current density $J_x$ at 55 K for two different devices. The widths of the transverse current leads were 100 $\mu$m (circles) and 30 $\mu$m (triangles). The solid line represents a fit to Eq. 1. Inset: The crossover transverse current density $J_c$ needed for the initial suppression of the depinning threshold $E_T$ increases with the value of $E_T$ at $J_x=0$. $J_c$ is plotted here as a function of $\sigma_0 E_T(0)$ for comparison with Eq. 2, where $\sigma_0$ is the conductance at bias fields much larger than $E_T$. Each data point was determined at a different temperature: from right to left, the temperatures were 25, 30, 35, 40, 45, 50 and 55 K.

FIG. 4. Dynamical model for the threshold field reduction: the vertical lines represent the charge density wavefronts which, if depinned, can move in the horizontal direction. The large filled circles represent the impurities or other defects in the crystal. The CDW sliding direction and the transverse current direction are indicated by the arrows. The small open circles ("a" and "b") represent the transverse single particle current. The deformations of the wavefronts due to momentum transfer with the transverse current are shown by the dotted lines.
$I_x = 800 \mu A$

$V_{f(e)}(I_x = 0)$
N. Markovic et al, Figure 1
I_x = 0

I_x = 190 \mu A
N. Markovic et al, Figure 2
The graph shows the relationship between $E_r / E_r(0)$ and $J_x (A/cm^2)$, with $J_c$ indicated at a certain point. The inset graph displays the relationship between $\sigma_0 E_r(0) (V/m\Omega cm^2)$ and $J_c (A/cm^2)$. The main graph includes data points represented by different markers, and the inset graph shows a linear trend.
N. Markovic *et al.*, Figure 3
CDW current

single-particle current

wavefronts
N. Markovic et al, Figure 4