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Charge density wave transport in $NbSe_3$ at low temperatures under high magnetic field

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Charge density wave (CDW) depinning and sliding regimes have been studied in $NbSe_3$ at low temperatures down to 1.5 K under magnetic field of 19 T oriented along the c-axis. We found that the threshold field for CDW depinning becomes temperature independent below $T_0 \approx 15$ K. Also CDW current to frequency ratio characterizing CDW sliding regime increases by factor 1.7 below this temperature. The results are discussed as a crossover from thermal fluctuation to tunneling CDW depinning at $T < T_0$. Besides, we found that CDW sliding strongly suppresses the amplitude of Shubnikov-de Haas oscillations of magnetoresistance.

$NbSe_3$ is a one of the most conventional material for studies of charge density wave (CDW) sliding regime. CDW dynamics is well documented in this material at high temperatures, above 30 K [1]. To the contrast, the low temperature CDW dynamics in $Nbse_3$ is nearly unstudied. That is related mainly with a fact that the threshold electric field E_t (or voltage V_t) for CDW depinning exponentially grows up with a decrease of temperature [2], while the electric resistance of the sample R drops down. Therefore, that is rather difficult to achieve threshold voltage at low temperatures avoiding Joule heating of the sample which is proportional to V^2/R. In a present paper we developed some experimental improvements to reduce heating effects. First, we studied CDW transport under high magnetic field which considerably, by factor of 10 at $H = 20$ T and $T = 1.5$ K, increases sample resistivity. Additionally, we used pulsed technique with current pulse width as short as 100 ns and high duty factor. Using those improvements we achieved CDW depinning and sliding regimes at low temperatures under conditions of highly eliminated heating effects.

The interest to the low temperature CDW dynamics in $NbSe_3$ is related with a possibility of macroscopic quantum tunneling of CDW in the impurity potential predicted by Bardeen [3] that is expected to be realized at low temperatures [4, 5]. Another interesting point is to study the effect of CDW sliding on Shubnikov – de Haas (ShdH) oscillations of magnetoresistance [6].

The experiments have been carried out on high quality $NbSe_3$ samples with residual resistance ratio above 100. The samples have been placed on sapphire substrate and covered by collodion to improve thermal contact with the substrate. The measurements of the I-V characteristics and their derivatives have been done by 4 probes method using computer controlled DC current source and nanovoltmeter. Pulsed measurements have been done with a use of generator of signals with a digitizing rate of 2 GHz and "LeCroy WR104Xi" oscilloscope with a band width of 1 GHz and digitizing frequency of 10 GHz. The measuring system allowed to measure resistance on current pulses of length less then 100 ns with a duty factor above 10^3. The measurements in high magnetic fields up to 21 T have been done in Grenoble National Lab of High Magnetic Field.

Figs.1a, b show two sets of differential I-Vs measured below 60 K down to 4.2 K. The threshold voltage V_t is characterized by sharp decrease of dV/dI with voltage. One can see that below 44 K V_t starts to increase rapidly up from 1 mV to about 6 mV at 33 K and then remains nearly unchanged with further temperature decrease down to 26 K. At lower temperatures the differential resistance below threshold rapidly drops down (Fig.1b) and below 12 K the $dV/dI(V)$ curves transform into wider curves with threshold of about 30 mV which again is nearly non-changed below 12 K down to 1.5 K. The temperature dependence $V_t(T)$ is plotted in semilog scale in Fig.1c. One can see that in average this dependence well follows exponential law $V_t \propto \exp(-T/T_0)$ found by Coleman et al. [2], but more detailed dependence shows two plateaus below 30 and 14 K.

As is well known, the CDW sliding is accompanied by narrow band noise (NBN) with a frequency proportional to the CDW velocity. The ratio of the CDW current to the NBN frequency is a constant characterizing sliding regime. The NBN frequency can be determined

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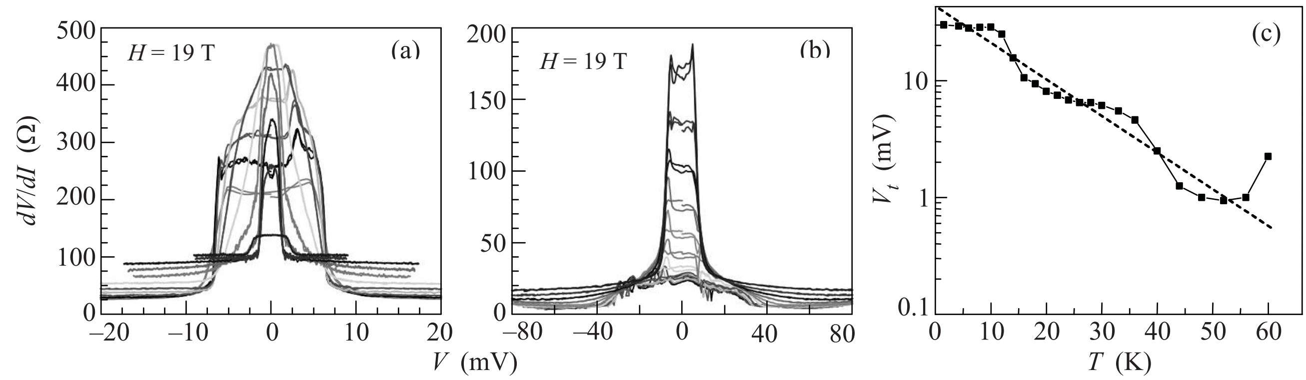

Fig.1. Sets of the differential I-Vs $dV/dI(V)$ measured at temperature intervals 60 – 26 K (a) and 24 – 4 K (b) and temperature dependence of threshold voltage V_t of $NbSe_3$ sample #3 under magnetic field of 19 T, $H \parallel c$. The straight line corresponds to the exponential dependence $V_t \propto \exp(-T/T_0)$ [2] with $T_0 \approx 15$ K. The threshold voltage has been determined on the level of one half of the total height of $dI/dV(V=0) - dI/dV$ $(V \gg Vt)$. Note that for some temperatures ($T = 24{-}12$ K) one can see two jumps of $dI/dV(V)$, corresponding to two thresholds.

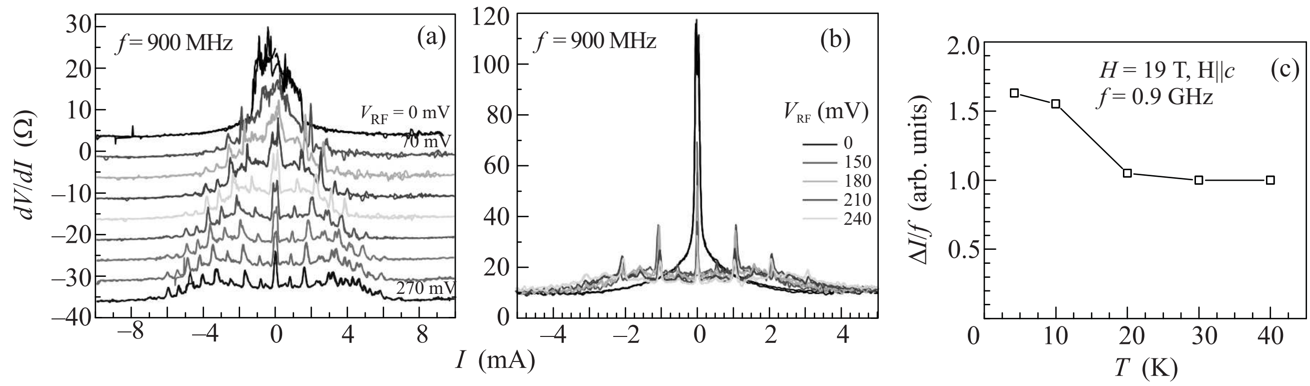

Fig.2. Shapiro step spectra of $NbSe_3$ sample #3 in magnetic field of 19 T oriented parallel to the c-axis at 4.2 K (a) and 20 K (b) under RF-radiation with frequency of 900 MHz. For the panel (a) RF-power is increased from top to bottom and curves are shifted down for clarity. Panel (c) shows the ratio of CDW current to frequency at various temperatures extracted from Shapiro step data at $H = 19$ T, $H \parallel c$-axis

directly from noise spectra or indirectly by observation of so-called Shapiro steps on the I-V characteristics under RF-field [1]. Shapiro steps appear when the frequency of external RF-field fex matches NBN frequency. Fig.2a show Shapiro step spectra of $NbSe_3$ sample under RF-field with a frequency of 900 MHz at 4.2 K. The top curve corresponds to the zero RF power. The threshold feature at $I = 1.7$ mA is clearly seen. With an increase of the RF power from top to bottom the threshold decreases and Shapiro steps develop as the peaks on $dV/dI(I)$ spectra. Observation of Shapiro steps provides a direct evidence of CDW sliding at low temperatures. For a comparison Fig.2b shows similar Shapiro spectra at 20 K. One can see that at high enough RF-power the spacing between zeroth, first and second peaks become equal and saturates with power. This fundamental value, ΔI, defines a current value which CDW carry by displacement on its one period for one cycle of the external frequency [1]. The ratio ΔI to f_{ex} is a constant associated with a charge of the one period of CDW.

A temperature dependence of this ratio (Fig.3c) is generally flat having some jump at temperature $T_0 \approx \approx 15$ K, below which the ratio increases by factor of 1.7. Amazingly, that dependence $V_t(T)$ also changes at that point and becomes nearly flat at lower temperatures. Therewith, this value, $T_0 = 15$ K, appears in the "averaged" exponential dependence of $V_t(T)$ at temperatures above 15K. All these findings indicate that the temperature T_0 is some characteristic temperature with different regimes of CDW pinning and sliding above and below T_0.

At low temperatures CDWs in $NbSe_3$ coexist with the uncondensed carriers localized at the pockets of the Fermi surface where the nesting condition for the CDW

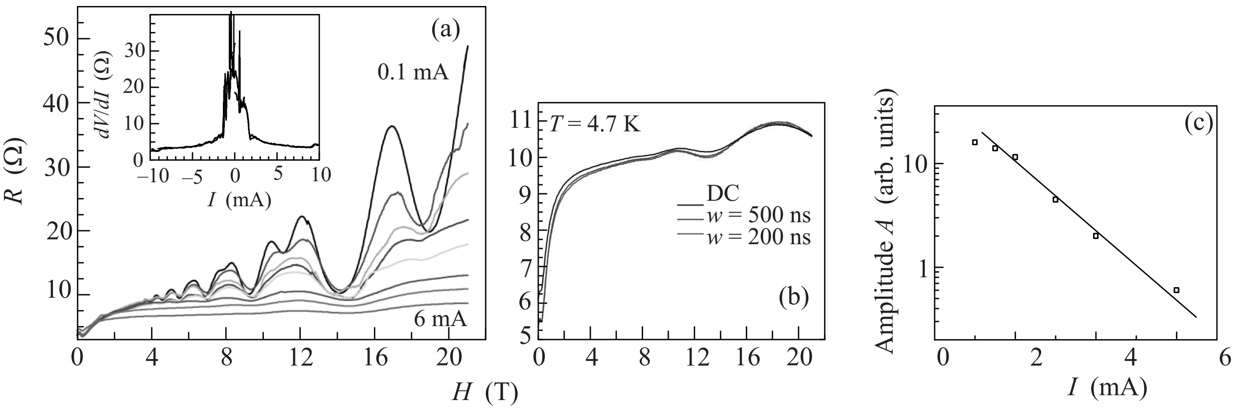

Fig.3. The variation of magnetoresistance of $NbSe_3$ sample # 3 at 1.5 K at various DC currents indicated in the plot (a), the insert shows correspondent $dI/dV(V)$ dependence at this temperature under magnetic field $H = 19$ T, $H \parallel c$. A comparison of magnetoresistance measured under DC and pulsed currents with duration of $w = 500$ ns and 200 ns of 9 mA(b) and a dependence of the amplitude of ShdH oscillation A at $H = 12$ T upon the DC current value above the threshold current for CDW depinning $I_t = 1.7$ mA (c). The straight line corresponds to the exponential law $A \propto \exp -(I/I_t)$

wave vector is not achieved. At low temperatures in high magnetic fields the spectrum of these free carriers becomes quantized. That manifests itself as ShdH oscillations of the magnetoresistance in $NbSe_3$. The pinned CDW does not affect essentially pocket carriers, while sliding CDW can increase their scattering and even drag them. In that case one can expect remarkable influence of CDW sliding on ShdH oscillations. There is only one paper [6] where ShdH oscillations have been studied in $NbSe_3$ at high currents, however, neither a threshold for the CDW sliding no heating effects have been clearly defined there. Here we justified a regime of CDW sliding at low temperatures by observation of sharp threshold voltage behaviour of the I-V characteristics and Shapiro step response to the RF-field. Fig.3a demonstrates a set of $R(H)$ dependences at various DC currents at 1.5 K, while the insert to Fig.3a shows the $dV/dI(I)$ at this temperature to show the current region for CDW sliding.

At low currents $R(T)$ dependences well reproduced behaviour that has been studied earlier [2, 6]. With current growth the oscillations become damped, first, slightly starting with currents of 0.5 mA and then more strongly at currents above 2 mA. Note that positions of minimums of oscillations do not change remarkably.

The insert to Fig.3a shows that the complete CDW depinning happens at 1.7 ma while some partial depinning accompanied by spikes on $dV/dI(I)$ occurs at lower currents. The mostly suppressed are maximums of oscillations, while at minimums magnetoresistance decreases a little. As a result at high currents the $R(H)$ dependence becomes very flat. A remarkable feature is that magnetoresistance decreases with current in the whole range of fields above 1 T. To estimate Joule heating DC measurements have been accompanied by pulsed measurements on short current pulses with repetition time exceeding time of pulses by three orders. Fig.3b shows comparison of $R(H)$ measurements on DC and pulsed currents of 9 mA with pulse duration of 500 ns and 200 ns. The resistance variation with changing from DC to the 500-ns pulsed currents is less than 0.5 Ohm and is nearly unchanged with further change to 200-ns pulse. That let us to estimate overheating temperature as being less than 2 K at current of 9 mA. For 6 mA current, the maximum current shown in Fig.3a, the overheating is estimated to be less than 1 K.

Thus, a remarkable feature observed is the strong damping of the amplitude of ShdH oscillations, A, induced by CDW sliding. Fig.3c shows that the corresponding $A(I)$-dependence above I_t follows the exponential law $A \propto \exp(-I/I_t)$.

We discuss now the possible reason for changing of CDW dynamics in $NbSe_3$ below $T_0 \approx 15$ K. The observed exponential dependence $V_t(T)$ at high temperatures is consistent with the thermal fluctuations behaviour of E_t derived by Maki [7]. In that model the threshold is determined by the thermal fluctuation of the phase of the CDW order parameter. At low temperatures, less then T_0, the energy of fluctuations is not enough to overcome CDW pinning potential, therefore, one can suggest tunneling mechanism for CDW depinning. That type mechanism of CDW depinning has been suggested by Bardeen [1, 8]. Thus one can consider T_0 as a crossover temperature from thermal fluctuations to tunneling mechanisms of CDW depinning. Similar crossover from thermal fluctuations to macroscopic quantum tunneling at low temperatures has been observed for the critical current behaviour in Josephson junctions [9]. The tunneling probability is temperature independent. That is also consistent with our observation of temperature independent behaviour of $V_t(T)$ below 15 K. In Bardeen's model the tunneling of CDW domain spreads in both directions along the chains. That provides current to frequency ratio twice bigger then for classically traveling CDW [8]. Though this point has been disputed later [10], our observation of the increase of this ratio by factor close to two below 15 K seems to be in agreement with Bardeen's model.

Let us consider now the observation of ShdH oscillation in the sliding CDW state. The strong effect of CDW sliding observed indicates the strong interaction of moving CDW with pocket carriers. That is most likely related with the CDW drag effect [11]. The energy transferring from sliding CDW to the carriers flattens their density of states peaked by Landau quantization thus resulting in suppression of the amplitude of ShdH oscillations. The important point is that the amplitude of ShdH oscillation, which is a single particle characteristic, exponentially suppressed with a scaling current I_t which is a dynamic characteristic of the CDW. That finding approves strong interaction of sliding CDW with uncondensed carriers. Recently the CDW drag effect in $NbSe_3$ has been also demonstrated with a use of Hall effect [12].

As shown in Fig.3a, a magnetoconductivity of the pocket carriers increases with current at all values of H. That also points to the CDW drag effect. Eventually, $R(H)$-dependence becomes very flat. That happens, when interaction of the pocket carriers with moving CDW becomes stronger then their coupling with magnetic field.

In a summary, we found that the CDW transport in $NbSe_3$ at low temperatures is characterized by temperature independent threshold for the CDW depinning and about twice bigger ratio of CDW current to frequency then at high temperatures. That points to the macroscopic CDW tunneling in $NbSe_3$ below 15 K. Besides, we found that the CDW sliding suppresses Shubnikov-de Haas oscillations of magnetoresistance. That is interpreted as a drag effect of moving CDW on pocket carriers.

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