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Quantized states of the charge-density waves in microcrystals of $K_{0.3}MoO_3$ and $NbSe_3$.

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One of the most interesting phenomena observed in the CDW compounds is the "quantization" of states associated with the "wave" nature of the CDW [1]. The states correspond with different number of wavelengths, *N*, in the sample, which should be integer, at least in the case of tight boundary conditions at the contacts [2] or at the sample ends. Transitions between the states go through separate phase-slip (PS) events adding or removing one wavelength.

The quantization appears on the interface between quantum and classical mechanics: the CDW is a quantum condensate, the wavelength being close to half the de Broglie wavelength of the Fermi-energy electrons, $\lambda = \pi/k_F$. At the same time, the discrete CDW states resemble those of a classical wave in a resonator.

The quantized value is the wave vector, *q*, of the CDW, whose magnitude can take the values $2\pi N/L$, where *L* is the sample length. This quantization has not been yet observed directly, *e.g.*, with diffraction techniques. However, one can observe it in conductivity, σ [1,2], though not only (in [3] thermopower steps were reported): each PS event changes the electron-hole balance and results in a shift of the chemical potential of the quasiparticles. One should keep in mind that perfect quantization of the *q*-vector can reveal itself in not exactly equidistant conducting states, as the conversion coefficient of δ*q* into δσ can depend on temperature and on the chemical potential position (i.e. on the CDW deformation).

Here we present the studies of nanosamples of $K_{0.3}MoO_3$ and $NbSe_3$ and demonstrate discrete values of conductivity corresponding with the quantized *q* values. We show that the effect is not only interesting in itself, but is helpful in determination of structural and transport properties of these compounds. In particular, from the jumps distribution in temperature, *T*, one can find the temperature change of the *q*-vector, and the value of δσ gives the mobility of quasiparticles. The resolution in *q* change appears comparable or exceeds that of the present diffraction techniques. As for mobility, for $NbSe_3$ the steps give the only direct way to distinguish the mobilities of different carriers.

$K_{0.3}MoO_3$

For the experiment needle-like transparent lamellas of $K_{0.3}MoO_3$ and whiskers of $NbSe_3$ from high-quality batches were selected. The sample thickness was of the order of 0.1 μm. The contacts were deposited with the laser-ablation technique, which is likely to provide tight boundary conditions for the CDW [2].

Fig. 1 shows fragments of σ(*T*) dependence for 3

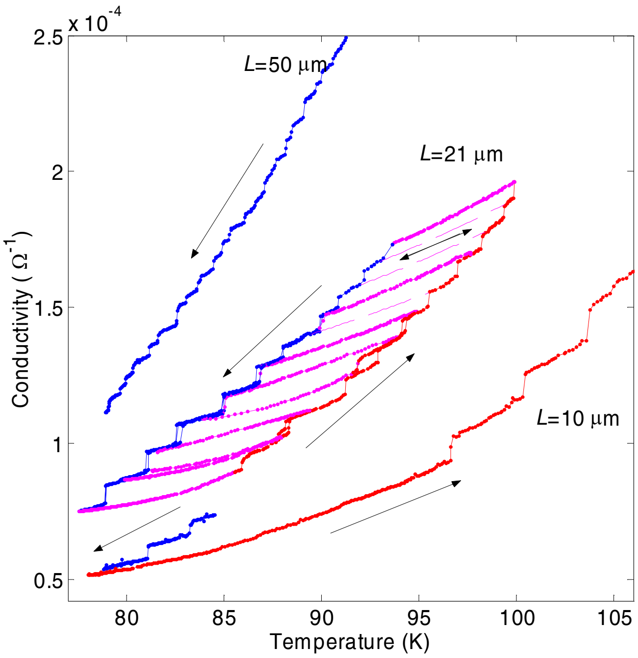

Figure 1. Fragments of the temperature dependences of conduction for different samples. The sample dimensions are: 21×5×0.3 μm3, 50×7×0.3 μm^3 (σ is multiplied by 1.5) and 10×5 μm^2 (σ is divided by 1.5). The arrows show the direction of temperature sweeps. The broken lines show the missed reversible fragments of the curves.

samples. Both cooling and heating curves show steps in σ. The jumps are regular in temperature. The height of the steps is approximately the same and is consistent with the value expected for a single PS event [1,2]. For the sample with contact separation *L*=21 μm the hysteresis loop is presented. For this sample it is clear that the steps reveal transitions between discrete states of the CDW. The σ(*T*) segments connecting the heating and the cooling edges of the loop are reversible, and no states can be achieved between these lines.

Once each jump corresponds with $\delta q = \pm 2\pi/L$, one can restore the *q* change counting the steps over a temperature span, keeping in mind that *q* decreases with cooling. Fig. 2 shows the *T* variation of the normalized value of the *q*-vector, $\delta q/q(0)$, where $q(0)=2\pi/(29.7$ Å$)$. With a single fitting parameter $\delta q(T)$ represents $q(T)$-$q(0)$. It follows activation law characterized with the energy ≈460 K. The X-ray diffraction results from [4] are also shown here together with the error bars. The resolution in *q* change based on the jumps counting is much higher.

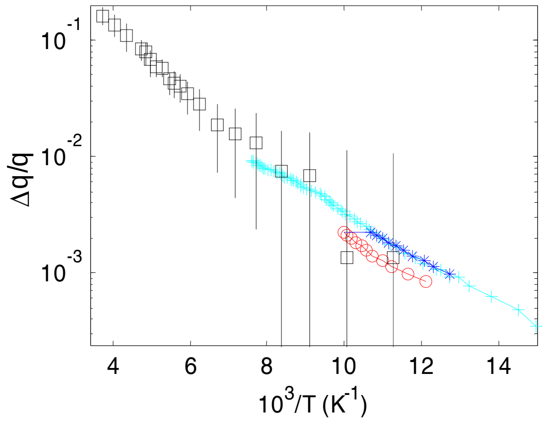

Figure 2. $\delta q/q$ change in BB calculated from $\sigma(T)$ on the assumption that at each step $|\delta q|=2\pi/L$. '+' – cooling in a wide temperature range, '*' and 'o' – cooling and heating in the narrow temperature range (see Fig. 1). The diffraction results [4] ('squares') are also shown (with the error-bars).

Each PS event results in the $\pm 2/L$ change of carriers concentration per chain. Knowing $\delta\sigma$ one can find the carriers mobility:

Equation 1. $\mu = \delta\sigma L^2 s_0/(2es)$,

where s is the cross-sectional area of the sample, s_0 – the area per chain. For BB the mobility found from the value of $\delta\sigma$, 10 cm^2/Vs, nearly coincides with the value provided by the Hall-effect studies, 13 cm^2/Vs [5].

$NbSe_3$

While for BB one can find the value of mobility from magnetotransport studies, it is a complex problem for $NbSe_3$, where 3 types of chains provide different carriers. The studies of PS gives a way to solve this problem.

Figure 3 shows a fragment of $\sigma(T)$ dependence for a NbS_3 nanosample for T in the range of the lower CDW; a polynomial is subtracted. The result looks as a number of lines fanning out with decreasing T. The obvious growth of $\delta\sigma$ at low T reveals the growth of the carriers' mobility (Eq. 1). The results for different samples are shown in the inset to Fig. 3 (together with the calculations [6]). No fitting parameters are involved. One can see drastic growth of μ at low T. Around 40 K it is in agreement with the model [6] but grows notably faster with cooling.

The high μ should be attributed to carriers particularly over type I chains. According to [6], these are pocket holes, as the contributions of thermally excited quasiparticles could be neglected below 50 K. According to [7], the pocket holes, having very low effective mass, are strongly different from the thermally excited quasiparticles. This feature makes $NbSe_3$ an outstanding compound not only within the CDW family.

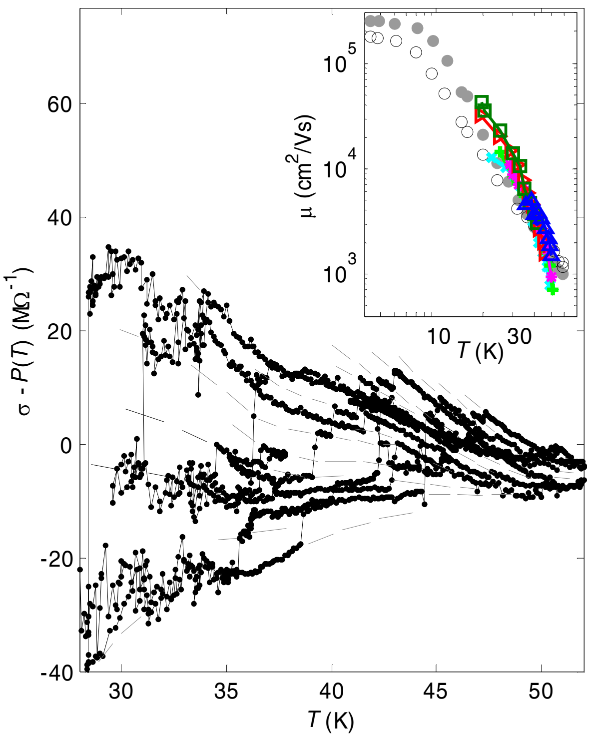

Figure 3. $\sigma(T)$ after subtracting a polynomial for a $NbSe_3$ sample (L=33 μm, s=0.03 μm^2). The broken lines are guides for eye. The inset shows the temperature dependence of mobility obtained from processing of 5 samples (L=29–62 μm). The closed circles (electrons) and open circles (holes) are taken from the model [6].

Conclusions

We have shown that BB and $NbSe_3$ nanosamples demonstrate discrete states revealing a specific for the CDW "quantization" of the q-vector. The effect provides a fruitful, and, in certain cases, indispensable technique for studies of superstructure evolutions and carriers mobilities.

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