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NARROW BAND NOISE IN SDW SLIDING

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Narrow band noise was observed in the spin-density-wave (SDW) phase of quenched $(TMTSF)_2ClO_4$, when electric current larger than the threshold for non-ohmicity was passed parallel to the one-dimensional axis. The noise frequency F increases linearly with the excess current density J_{SDW} with a slope $F/J_{SDW} = 240\,\mathrm{kHz}\,(\mathrm{Acm}^{-2})^{-1}$. It is confirmed that the non-linear excess current is carried by the SDW condensate and that the narrow band noise is generated by the sliding motion of the SDW.

IN THE past fifteen years, the collective sliding of charge-density-wave (CDW) condensate was well established by a great deal of investigations in several quasi-one-dimensional conductors. Since the spin-density-wave (SDW) state was discovered in organic $(TMTSF)_2X$ salts, the sliding motion of SDW have been also looked for experimentally, because of its condensed state similar to that of the CDW. In the SDW phase of $(TMTSF)_2PF_6$, remarkable increase of conductivity was found [1] with increasing external electric field and it was suggested that the increase is associated with the SDW sliding. But it became clear from subsequent investigations [2, 3] that the non-linear conductivity comes rather from the hot electron effect. Osada *et al.* proposed [4] the sliding of SDW with the non-ohmic conductivity in the magnetic field-induced SDW phases of $(TMTSF)_2ClO_4$ but they observed the non-linearity only in the perpendicular component.

Recently Tomic *et al.* observed [5] the non-linear conductivity along the one-dimensional axis with a clear threshold field in $(TMTSF)_2NO_3$ and a nearly temperature-independent threshold field was explained with the strong pinning theory of SDW [6]. We also found [7] the non-linear conductivity with a threshold field in the SDW phase of quenched $(TMTSF)_2ClO_4$ but we observed rather large temperature dependence of threshold field. These two results are supposedly indicative of the sliding motion of the SDW condensate, but the non-ohmic d.c. conductivity alone cannot provide its evidence. Clear result has never been obtained yet in the SDW systems as for other characteristic phenomena associated with the sliding motion such as the narrow band noise and the a.c.–d.c. interference, which are always observed in the CDW sliding.

We investigated carefully the voltage noise spectra in the quenched state of $(TMTSF)_2ClO_4$, and found a peak structure when the current bias was larger than the threshold for the non-linear conductivity. This noise peak is confirmed as the narrow band noise in the SDW sliding. In this paper we report on the results of noise measurement and discuss the sliding motion of SDW.

The standard four probe method was used in the course of the present measurement for $(TMTSF)_2ClO_4$ single crystal samples. Electric leads of $20\,\mu$m annealed gold wire were attached with silver paint onto gold-evaporated contacts. Cross section and distance between voltage contacts of the sample, with which the following results were obtained, were $0.20 \times 0.10\,\mathrm{mm}^2$, and 4.2 mm, respectively. To avoid cracking, the sample was pre-cooled down to 80 K in 3 days. We observed no detectable resistance jump in the cooling process. The quenched state was brought about by immersing the sample into liquid helium after prolonged holding at 40 K. The quenching rate at 20 K, which was monitored with a silicon-diode thermometer near the sample, was larger than $100\,\mathrm{K\,s}^{-1}$. The voltage noise was observed most clearly at the lowest temperature 1.16 K, maintained by evacuating liquid helium bath with a rotary vacuum pump and a mechanical booster pump. The noise spectra of voltage was analyzed under constant d.c. current with an analog spectrum analyzer and a hand-made pre-

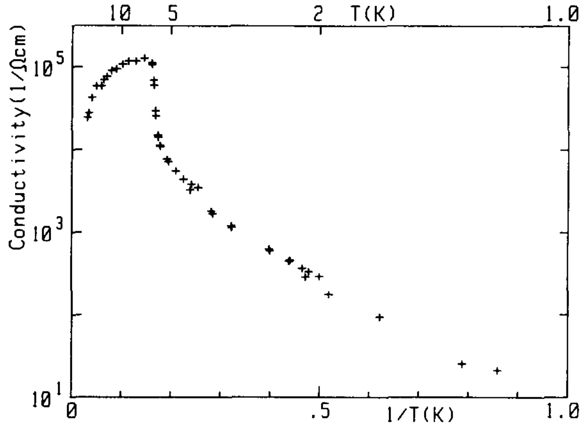

Fig. 1. Temperature dependence of ohmic conductivity of $(TMTSF)_2ClO_4$ sample. The SDW transition temperature is 5.9 K and the SDW gap 2Δ is estimated as 17.3 K.

amplifier. To exclude spurious noises, dry cell was used for current supply with a large series resistance. After the noise measurement, the temperature dependent ohmic conductivity was measured with warming the sample and the SDW transition temperature was determined from it.

Figure 1 shows the temperature dependence of the ohmic conductivity. The SDW transition temperature T_N is 5.7 K. The SDW gap 2Δ is obtained as 17.3 K from the thermally activated behaviour of the conductivity below 3 K. The ratio $2\Delta/T_N = 3.0$ is larger than our previous result (2.6) [7] and is rather near to the BCS value 3.5. We discussed the smaller ratio as due to the inhomogeneous quenching rate and the internal strain. In the present experiment, we could not detect any resistance jump in the cooling process and obtained the same conductance at room temperature after measurements at low temperature as before cooling. Moreover, we obtained the resistivity ratio $\varrho_{RT}/\varrho_{min} = 200$, which is quite large as for quenched state of $(TMTSF)_2ClO_4$. These results indicate that the present sample suffers much less strain. Therefore the ratio, near the mean field value, suggests that the one-dimensional fluctuation is weak in the present SDW material. But more precise discussion is still open for successive investigations.

In Fig. 2 is shown the non-linear d.c. conductivity obtained at 1.16 K. From comparison with pulse conductivity data, we confirmed that the Joule heating effect is negligible in this temperature range. The threshold field is obtained as $E_T = 11\,\mathrm{mV\,cm^{-1}}$, which is lower than our previous result. The fractional conductivity increase above the threshold was much larger than those of other examined samples. These results suggest that the transport behaviour of the present sample shows the essential property of the SDW state free from some defects accompanied by the

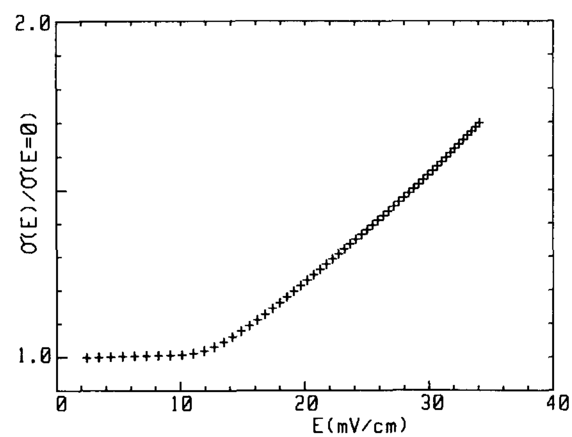

Fig. 2. Electric field dependence of conductivity at 1.16 K. The conductivity increases sharply above a threshold field $E_T = 11\,\mathrm{mV\,cm^{-1}}$.

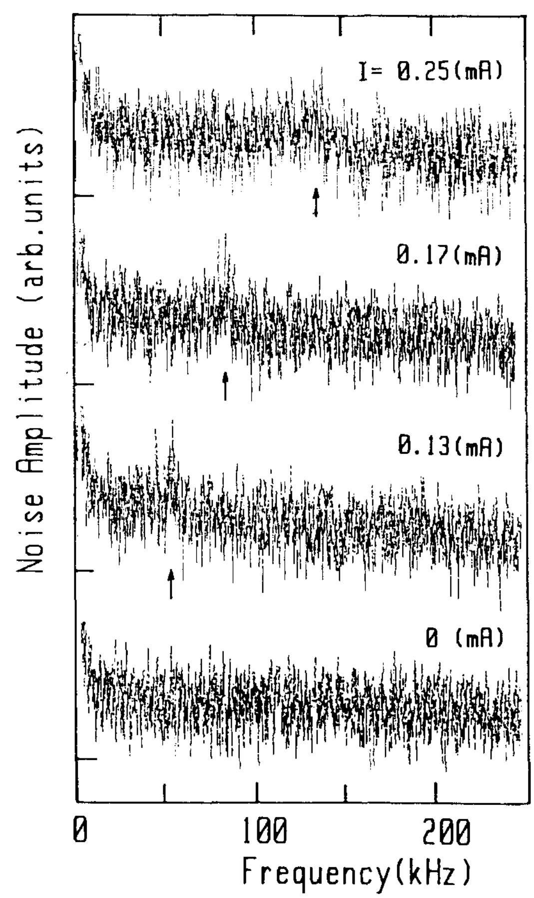

Fig. 3. Typical noise spectra of voltage for constant current. A peak structure (indicated by arrows) appears just above the threshold current ($I_T = 0.05\,\mathrm{mA}$) and the peak frequency increases with bias current.

resistance jump. We reproducibly found that the threshold field decreases continuously with decreasing temperature down to $T_N/5$. This behaviour is somewhat different from that observed in $(TMTSF)_2NO_3$ [5] and is not consistent with the pinning theory of SDW [6]. The detailed temperature dependence of threshold field will be discussed elsewhere.

We analyzed the voltage signal under the current control condition and obtained a peak structure in the voltage noise spectra as shown in Fig. 3. This peak appears just above the threshold current and the peak frequency increases with increasing external bias current. The peak power is much lower than that of the narrow band noise in the CDW sliding. Neither higher harmonics nor hump of the noise level at low frequency (broad band noise) was observed. In Fig. 4, we plot the frequency F against the excess current I_{SDW}, which is assumed to be carried by the SDW condensate and is estimated from the non-linear I–V curve, as

$$I_{SDW} = I - V/R_n, \tag{1}$$

where R_n represents the ohmic resistance below the threshold. The peak frequency F increases linearly with the excess current I_{SDW}.

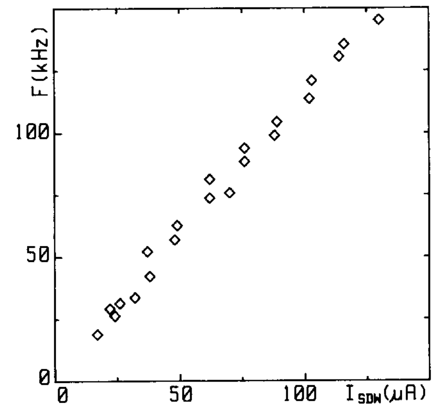

Fig. 4. Frequency of voltage noise peak F against excess current I_{SDW}. The peak frequency increases linearly with the excess current.

According to the washboard model for sliding, the ratio of the fundamental frequency F to the excess current density J_{SDW} can be described with the electronic density condensed to the SDW n_{SDW} as

$$F/J_{SDW} = 1/(en_{SDW}\lambda_{pin}), \tag{2}$$

where λ_{pin} represents the periodic length of the pinning potential. For the impurity pinning of CDW λ_{pin} is just equal to the wave length of CDW λ_{CDW}. Unlike the case of CDW, normal impurities cannot pin the SDW in the first order [8] and the second order pinning gives $\lambda_{pin} = (1/2)\lambda_{SDW}$. For magnetic impurities, the lowest order pinning arises similarly to the CDW case and λ_{pin} is equal to λ_{SDW}.

Our result, shown in Fig. 4, clearly reveals the linear relation of equation (2). From its slope, $F/J_{SDW} = 240\,\mathrm{kHz}(\mathrm{Acm}^{-2})^{-1}$ is obtained. We can estimate $n_{SDW}(0) = 1.44 \times 10^{21}\,\mathrm{cm}^{-3}$ at 0 K, assuming the full charge transfer from ClO_4 molecules to the TMTSF one-dimensional metallic band and the perfect nesting of the Fermi surface. Accordingly, we obtain $\lambda_{pin} = 1.8\,\mathrm{Å}$ for the present sample, using $n_{SDW}(0)$ for that at 1.16 K ($\sim T_N/5$). In $(TMTSF)_2X$ salts, it is supposed that the wave number of SDW along the one-dimensional axis is almost equal to $(1/2)a^*$ and correspondingly the wave length of SDW λ_{SDW} is about $2a = 14.5\,\mathrm{Å}$ in $(TMTSF)_2ClO_4$. Though the value of λ_{pin} is deduced above is smaller than $(1/2)\lambda_{SDW}$ or λ_{SDW}, qualitative consistency with these expected values is found from the following argument. A smaller value of pinning period has been observed frequently in cases of the CDW. It has been explained [9] by the underestimated excess current density because in some parts of the sample volume the CDW is pinned even above the observed threshold field; the high one-dimensionality can bring about such an inhomogeneous motion of the CDW quite easily. The conductivity of $(TMTSF)_2ClO_4$ shows a large anisotropy. We arranged four leads on a–b surface of sample along the a axis. Together with the large anisotropic conductivity, the electrode arrangement presumably causes the inhomogeneous current flow and as a result the SDW may be pinned even above the observed threshold field near the opposite surface, where quite weak electric field arises presumably. The relatively broad width of observed noise peak, which increases with the excess current, may indicate such an inhomogeneous flow of the SDW current. It is probable that the SDW slides only through the limited cross sectional area. If this is the case, we should use a larger value for J_{SDW} and the consistency with the expected values is improved. Therefore, the value of λ_{pin} obtained in this work should be regarded as the lower limit. In the present situation, we cannot determine exactly whether the pinning period is $(1/2)\lambda_{SDW}$ or λ_{SDW} and improvement of the experiments including the electrode arrangement is necessary. However, it is obvious that such a pinning mechanism plays an essential role in the generation of observed noise peak and that it corresponds to the narrow band noise in the SDW sliding. Our present results indicate unambiguously that the excess current above the threshold is carried by the SDW condensate; the SDW can move collectively with the Frohlich mechanism.

Neither higher harmonics nor broad band noise was observed. The amplitude of narrow band noise itself is very small. These may be attributed to the size effect, which was discussed [10] for the amplitude of narrow band noise in the CDW systems. On the other hand, it is possible that these are the characteristics of the SDW pinning unlike the case of CDW. Experiments are under progress to find if higher harmonics are only hidden in back ground noises.

In conclusion, we observed for the first time the narrow band noise in the SDW phase of quenched $(TMTSF)_2ClO_4$. This gives the direct evidence of the sliding motion of SDW. The obtained pinning period is about 1/8 of the wave length of SDW and is qualitatively explained with the impurity pinning mechanism.

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