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Effect of quenching rate on SDW dynamics in $(\text{TMTSF})_2\text{ClO}_4$

K. NOMURA, T. ONODERA, T. SHIMIZU, T. SAMBONGI, M. TOKUMOTO*, N. KINOSHITA* and H. ANZAI**

Department of Physics, Hokkaido University, Sapporo 060, Japan

** Electrotechnical Laboratory, Tsukuba, Ibaraki 305, Japan*

*** Department of Material Science, Himeji Institute of Technology, Kamigohri, Hyogo 678-12, Japan*

The pinning mechanism of SDW condensate associated with the imperfect nesting effect was investigated with the measurement of the temperature dependence of the threshold electric field E_T for the depinning of SDW in $(\text{TMTSF})_2\text{ClO}_4$ for various anion quenching rates. The relatively strong temperature dependence of E_T observed in the most rapidly quenched phase with $T_C=5.85$ K is described by the 3-dimensional impurity weak pinning. With decreasing the quenching rate, the temperature dependence of E_T becomes gradual for $T_C>3$ K. This behavior is explained by the change of pinning mechanism to the strong pinning. For much lower quenching rate ($T_C<3$ K), the temperature dependence of E_T becomes steeper again and is attributed to the increase of imperfectness of nesting of Fermi surface. It is understood that the SDW pinning is provided by the disordered array of anion.

1. INTRODUCTION

The collective sliding mode of spin-density wave (SDW) condensate have been investigated extensively in the SDW phase of $(\text{TMTSF})_2\text{X}$ salts. The early observation of the non-linear conductivity was explained rather by the one-electron effect than the collective mode, as the threshold electric field was absent unlike the case of the charge-density wave. Tomić et al. [1] reported the non-linear conductivity with a clear threshold field for the depinning of SDW in $(\text{TMTSF})_2\text{NO}_3$. Similar threshold behavior was also found in quenched $(\text{TMTSF})_2\text{ClO}_4$ [2] and $(\text{TMTSF})_2\text{PF}_6$ [3] in succession. The narrow band voltage noise was successfully measured in the SDW phase of $(\text{TMTSF})_2\text{ClO}_4$ [4]. The narrowing of the NMR line structure associated with the SDW by its sliding motion was also observed in $(\text{TMTSF})_2\text{ClO}_4$ [5]. The sliding mode of SDW was established by these experiments unambiguously.

It is important to clarify the pinning mechanism for better understanding of the dynamics of SDW. The pinning of SDW by non-magnetic impurities is of second order in contrast with the case of the charge-density wave, because the charge density is uniform in space for the SDW state. Huang et al. [6] calculated the threshold electric field E_T for the impurity pinning within the mean field treatment and tried to explain observed temperature dependence of E_T in several $(\text{TMTSF})_2\text{X}$ salts. The temperature dependence of the order parameter, which is determined by the two-dimensionality of initial electronic band, plays an essential role in their theory. With increasing the two-dimensional character in the electronic band, the nesting of Fermi surface becomes less perfect. It is expected that with increasing the imperfectness of nesting, the temperature dependence of E_T becomes steeper for both the strong and the weak impurity pinning.

In $(\text{TMTSF})_2\text{ClO}_4$ salt, there is the orientational order transition of non-centrosymmetric anion ClO_4^- around 24 K. The degree of anion ordering determines the ground state through the two-dimensionality in electronic band. When the sample is cooled down slowly through this temperature, the superconducting phase appears. On the other hand, in the rapidly quenched phase the SDW state is stabilized as the ground state. It was reported that with decreasing the quenching rate, the SDW transition temperature T_C decreases. It is accepted that such a decreasing of T_C is provided by the

decreasing of perfectness of Fermi surface nesting. Accordingly $(\text{TMTSF})_2\text{ClO}_4$ is a suitable materials for investigation of the imperfect nesting effect.

In order to clarify the imperfect nesting effect to the SDW pinning, we investigated the temperature dependence of threshold electric field E_T with varying the quenching rate systematically in $(\text{TMTSF})_2\text{ClO}_4$. In this article, we report the observed behavior of E_T and discuss the pinning mechanism by the disordered array of anion.

2. EXPERIMENTAL

Crystal of $(\text{TMTSF})_2\text{ClO}_4$ was grown by the electro-chemical method. We investigated two sample from different batches; #1 and #2. The electric conductivity was measured mainly by the pulse method with standard four-probe in order to avoid Joule heating effect. Electric lead of 10 μm gold wire was attached to gold evaporated pads with silver paint. Typical sample cross-section and distance between voltage leads were $0.2 \times 0.1 \times 5 \text{ mm}^3$. In the initial cooling stage down to 77 K, the cooling rate was controlled less than 4 K/h to avoid the occurrence of resistance jump. The quenching was done by immersing the sample into liquid helium directly after pre-holding at 40 K. The quenching rate was defined as the rate of decreasing temperature through the anion ordering temperature 24 K. This rate was monitored by the silicon-diode thermometer. The SDW transition temperature was determined from the peak of $d(\ln R)/d(1/T)$, where R is the ohmic resistance.

3. RESULTS AND DISCUSSION

The quenching rate was controlled manually in the empirically determined manner. The observed SDW transition temperature T_C is shown as a function of the quenching rate in Fig. 1. For the quenching rate higher than 50 K/h, T_C is almost unchanged. With decreasing the quenching rate below 50 K/h, T_C begins to decrease as shown in Fig. 1. We confirmed that T_C is systematically controlled by the quenching rate in our present method. This decreasing of T_C is explained by the increase of the imperfectness parameter ϵ_0 defined as

$$\epsilon_0 = t_b^2 \cos(ak_F) / 2t_a \sin^2(ak_F)$$

where t_a and t_b are transfer energies along the a - and b -axis, respectively. The ratio of ϵ_0 to the order parameter at 0 K Δ is a fundamental parameter and the SDW phase disappears for $\epsilon_0/\Delta > 1$. It is accordingly understood that with increasing the anion ordering the nesting becomes less perfect.

Fig. 1 SDW transition temperature vs. anion quenching rate.

Fig. 2 Normalized excess conductivity vs. electric field for the rapidly quenched phase in #1 sample.

In Fig. 2, we show the field dependent normalized conductivity $\{\sigma(E)-\sigma(0)\}/\sigma(0)$ in the rapidly quenched SDW phase with $T_C=5.85$ K measured in #1 sample for several temperatures. Each curve is offset by 0.1 for clarity. The conductivity is increasing above the well-defined threshold electric field E_T . We determined E_T as the intersection of the ohmic conductivity line and the extrapolated line from $2E_T$ as described in the previous article [7].

The temperature dependence of E_T in #1 sample is shown for each quenching rate in Fig. 3. In the figure, the quenching rate is denoted as the transition temperature T_C . For the most rapid quenching with $T_C=5.85$ K, the temperature dependence of E_T is relatively steep and is consistent with the previous result [7]. This temperature dependence is well fitted by the theoretical curve of 3-dimensional weak impurity pinning with imperfectness parameter $\epsilon_0/\Delta=0.7$, where the order parameter is deformable in 3-dimensional space. With lowering T_C , the temperature dependence of E_T becomes gradual. It is expected from the mean field treatment that the temperature dependence of E_T become steeper along with the increase of imperfectness of nesting in the 3d weak pinning. The observed curve shows an opposite behavior and is fitted rather by the strong pinning with $\epsilon_0/\Delta=0.8$ than the weak one as shown in Fig. 3. The strong pinning occurs when the individual impurity potential is strong and the impurity concentration is small. In quenched $(\text{TMTSF})_2\text{ClO}_4$, the impurity potential is assigned to the disordered array of anion, which breaks the translational symmetry. It is naturally expected that the disorder density is smaller for a phase with lower T_C . It is understand the weak pinning changes to the strong one, with decreasing disorder.

Fig. 3 Temperature dependence of E_T in #1 sample for various quenching rates and fitting to the theoretical calculation. The quenching rate is denoted by T_C .

Fig. 4 Temperature dependence of E_T in #2 sample for various quenching rates and fitting to the theoretical calculation.

Further slow quenching phase was examined in #2 sample. The temperature dependence of E_T is shown in Fig. 4. In this sample, E_T shows an anomalous decrease at high temperature region. We observed that the fractional excess conductivity is decreasing abruptly in this anomalous temperature region. It is deduced that the SDW is sliding in only limited volume of sample at high temperature region. Some inhomogeneity in the sample may be responsible for such an anomalous behavior. On the other hand, the behavior at low temperature region is essentially the same as #1 sample and other samples investigated in the previous work. Accordingly, we discuss here only the result in the low temperature for #2 sample. We observed essentially the same temperature dependence of E_T as #1 sample for higher T_C than 3.5 K, although only the result for $T_C=5.85$ K is shown in Fig. 4 for clarity. With lowering T_C below 3.5 K, the temperature dependence of E_T becomes steeper again. The absolute magnitude of E_T at low reduced temperature ($T/T_C=0.3$) decreases with lowering T_C . Within the strong pinning regime, the temperature dependence of E_T is dominated by that of order parameter $\Delta(T)$. As shown in Fig. 4, the observed temperature dependence is well reproduced by the theoretical

calculation taking account of the imperfectness parameter.

Table 1 Imperfectness parameter ε_0/Δ estimated from T_C and the temperature dependence of E_T

$T_C(K)$	ε_0/Δ	
	from T_C	from E_T
5.85	0.7	0.7
4.2	0.9	0.8
3.5	0.95	0.85
3.2	0.96	0.92

In table 1, we give estimated values for the imperfectness parameter ε_0/Δ from the relation between T_C and ε_0/Δ in the mean field theory together with that used in the fitting of observed temperature dependent E_T . The agreement is satisfactorily and it strongly supports the above mentioned mechanism. The absolute magnitude of E_T decreasing with T_C is also reasonably explained by the strong pinning where E_T is proportional to the impurity concentration, because the disorder density is expected to be smaller for lower T_C . The SDW pinning in quenched $(TMTSF)_2ClO_4$ is totally understood as the impurity pinning by the disordered array of anion in connection with the imperfect nesting effect.

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