ELSEVIER

Synthetic Metals 120 (2001) 897–898

SYNTHETIC METALS

www.elsevier.com/locate/synmet

SDW gap in $(TMTSF)_2PF_6$: STM spectroscopy

K. Ichimura[a*], M. Kobayashi[a], K. Nomura[a], T. Hanajiri[b], J. Yamada[b], S. Nakatsuji[b], H. Anzai[b]

[a]*Division of Physics, Hokkaido University, Sapporo 060-0810, Japan*

[b]*Department of Material Science, Himeji Institute of Technology, Hyogo 678-1201, Japan*

Abstract

The SDW phase of $(TMTSF)_2PF_6$ was investigated by the electron tunnelling spectroscopy using a low temperature STM. Below T_{SDW}=12 K, the tunnelling differential conductance shows the energy gap structure associated with the SDW state. The functional form of the spectrum is explained by the mean field theory for quasi-one dimensional conductors. We obtained the SDW gap Δ_{SDW}=2.3 meV and the imperfect nesting parameter ε_0=1.8 meV. The temperature dependence of the zero bias tunnelling conductance below T_{SDW} is also explained by the electronic density of states for the imperfect nesting. The pseudogap structure was observed above T_{SDW}.

Keywords: atomic force microscopy, scanning tunnelling microscopy, metal-insulator phase transitions

1. Introduction

A lot of quasi-one dimensional conductors undergo the density wave (DW) state, which is the charge density wave (CDW) or spin density wave (SDW), resulting from the nesting of the Fermi surface [1]. In the DW state, the energy gap is formed at the Fermi level similarly to superconductors. The electron tunnelling spectroscopy is useful in investigating such condensed states as the DW and superconducting state since the electronic density of states can be obtained directly with high energy resolution [2]. Among tunnelling methods, an STM has advantages due to non-contacting tip configuration. There is less disturbance to the sample surface.

In organic quasi-one dimensional conductors, the superconducting phase of $(TMTSF)_2ClO_4$ was studied by the junction method [3]. We reported the tunnelling spectroscopy using an STM on the SDW phase of $(TMTSF)_2PF_6$ and indicated that the tunnelling spectrum is consistent with the electronic density of states for the imperfect nesting DW state [4].

In this article, we present the tunnelling spectrum obtained by an STM at various temperature and discuss about the pseudogap above the SDW transition temperature.

2. Experimental

Single crystals of $(TMTSF)_2PF_6$, which are ribbon shape along the *a*-axis, were synthesized electro-chemically. The SDW transition temperature was determined as T_{SDW}=12 K from the resistive transition. As grown surface of the *a-b* plane was investigated by a low temperature STM. The tunnelling differential conductance was directly obtained by the lock-in detection.

3. Results and Discussion

Figure 1 shows tunnelling differential conductance at 4.2 K. The spectrum clearly shows the energy gap structure associated with the SDW state. The conductance within the bias voltage of V=4 mV is well reduced. The conductance

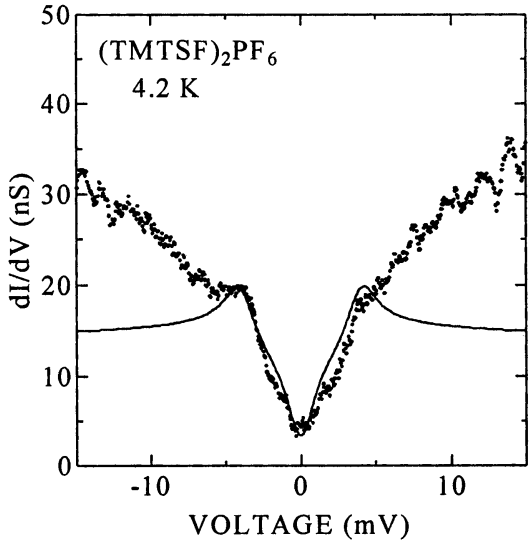

Fig. 1. The tunnelling differential conductance at 4.2 K. The solid line represents the calculation described in the text with parameters of Δ_{SDW} =2.3 and ε_0=1.8 meV.

* Corresponding author. E-mail: ichimura@sci.hokudai.ac.jp

PII: S0379-6779(00)00930-9

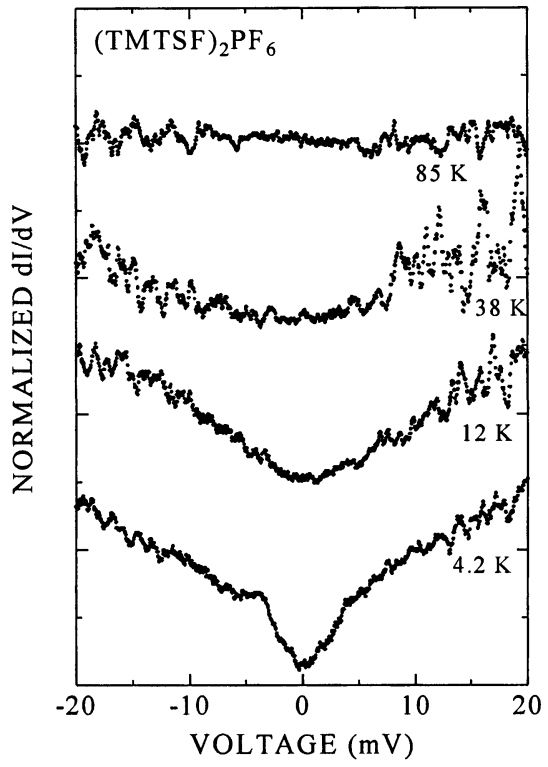

Fig. 2. Temperature dependence of the tunnelling spectrum. The zero conductance line of each curve is shifted by two divisions for clarity.

at zero voltage is abut 20 % of that at V=7 mV. In contrast to the isotropic gap case, the conductance inside the gap is finite suggesting the gap anisotropy. In explaining the gap anisotropy, we examine the mean field theory for quasi-one dimensional conductors [5]. The calculated curve, which is based on the electronic density of states for the imperfect nesting DW state [6], is shown in Fig. 1 as the solid line. The fitting is satisfactory. Both the zero bias conductance and a slight constriction near V=1 mV are reproduced by the calculation taking into account the thermal smearing. From the fitting, we obtain the SDW gap parameter Δ_{SDW} and the imperfect nesting parameter ε_0 as 2.3 and 1.8 meV, respectively. The transition temperature for the perfect nesting T_{c0} is estimated as T_{c0}=15 K from the mean field relation of $2\Delta_{SDW}/k_BT_{c0}$=3.52. These parameters are almost consistent with that in our previous report [4]. It is confirmed that the density of states for the SDW phase is explained by the mean field theory with the imperfect nesting.

We found the pseudogap structure above T_{SDW}. Figure 2 shows the temperature dependence of the tunnelling spectrum. At T=85 K, the conductance is flat suggesting the metallic phase. Below T=80 K, the spectrum shows the dip structure around the Fermi level. The conductance near zero voltage decreases with decreasing temperature. At T_{SDW} of T=12 K, the SDW gap structure is unclear. Far below T_{SDW}, the gap structure associated with the SDW state becomes pronounced.

In order to discuss abut the origin of the pseudogap, we plot the temperature dependence of the zero bias conductance which is normalized by the conductance at

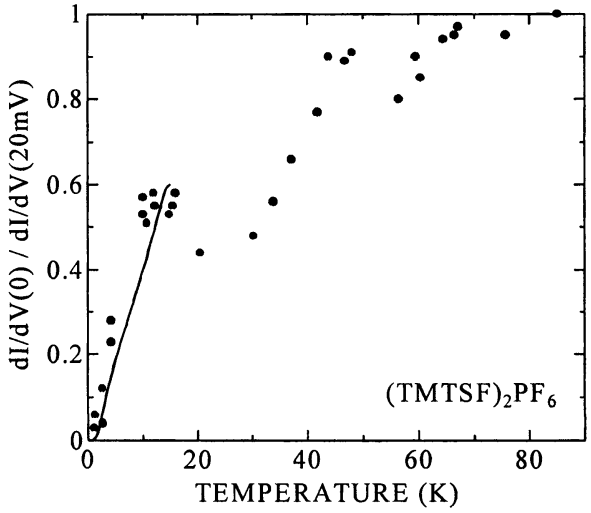

Fig. 3. Temperature dependence of the normalized zero bias conductance. The solid line represents the calculation described in the text.

V=20 mV in Fig. 3. The zero bias conductance decreases gradually with decreasing temperature below 80 K. There is a shoulder around T_{SDW}=12 K. Below T_{SDW}, the zero bias conductance decreases rapidly associated with the development of the SDW gap structure. This temperature dependence below T_{SDW} is explained by the thermal smearing of the electronic density of states for the SDW phase with parameters of Δ_{SDW}=2.3 and ε_0=1.8 meV obtained above. The solid line in Fig. 3 represents the calculation in which the temperature dependence of Δ_{SDW} is taking into account. It is suggested that the SDW gap vanishes at T_{SDW}. We conclude therefore that the decrease of the electronic density of states around the Fermi level above T_{SDW} is not due to the SDW gap. Moreover, a clear anomaly around T_{SDW} suggests that the pseudogap is not due to the fluctuation effect.

For the normal phase of $(TMTSF)_2PF_6$, Schwartz *et al.* [7] reported that the optical conductivity spectrum shows the drastic deviation from a simple Drude response. They explained such a non-metallic like behaviour in a view of the Tomonaga-Luttinger liquid. The pseudogap observed in the present tunnelling spectrum might have a relation to the deviation from the Drude response in the optical conductivity. We are now searching for the origin of the pseudogap.

Acknowledgement

This work was carried out as a part of 'Research for the Future project, JSPS-RFTF97P00105, supported by Japan Society for the Promotion of Science.

References

[1] G. Gruner, Density Waves in Solids, Addison-Wesley, 1994.
[2] I. Giaever, Phys. Rev. Lett., 5 (1960) 147.
[3] H. Bando, K. Kajimura, H. Anzai, T. Ishiguro, G. Saito, Mol. Cryst. Lig., 119 (1985) 41.
[4] K. Ichimura, O. Abe, K. Nomura, S. Takasaki, J. Yamada, S. Nakatsuji, H. Anzai, Synth. Metals, 103 (1999) 2097.
[5] K. Yamaji, J. Phys. Soc. Jpn., 51 (1983) 1861.
[6] X. Z. Huang, K. Maki, Phys. Rev. B, 40 (1989) 2575.
[7] A. Schwartz, M. Dressel, G. Gruner, V. Vescoli, L. Degiorgi, T. Giamarchi, Phys. Rev. B, 58 (1998) 1261.