STM Spectroscopy on Ba_8Si_{46}

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Abstract

Superconducting phase of silicon clathrate Ba_8Si_{46} was studied by the tunneling spectroscopy using STM. The energy gap structure associated with the superconducting state was observed clearly. The functional form of the tunneling spectra is explained by the model, in which the gap is assumed to be finite and has an anisotropy. According to the model, in which the gap varies depending on the direction in $\boldsymbol{k}$-space, we obtain gap parameters as Δ_{min}=0.45 meV and Δ_{max}=1.5 meV.

Key words: superconductivity; silicon clathrate; STM; electron tunneling

Since the synthesis of $Ba_6Na_2Si_{46}$ [1], a lot of attention has been given to the superconductivity in silicon clathrates because it is the first superconducting material based on sp^3 Si covalent bonding. Recent synthesis of bulk Ba_8Si_{46} by Yamanaka *et al.* [2] gives an opportunity to carry out various measurements.

The symmetry of the pair wave function is an important clue to clarify the mechanism of the superconductivity. For the pairing symmetry, the s-wave pairing is suggested in Ba_8Si_{46} by high-resolution photoemission spectroscopy [3]. The electron tunneling spectroscopy is useful method in searching for the mechanism of the superconductivity since the electronic density of states can be obtained directly in high energy resolution. Scanning tunneling spectroscopy (STS) has an advantage because of its non-contacting tip configuration.

In this article, we report the electron tunneling spectroscopy on Ba_8Si_{46} using STM and discuss the symmetry of the pair wave function.

A single phase of Ba_8Si_{46} was synthesized under high pressure [2]. The superconducting transition temperature T_c was determined as 8.0 K from the magnetic susceptibility measured by SQUID magnetometer with applying field of 10 Gauss. A clean surface was prepared by cleaving immediately before the STM measurement. The tunneling differential conductance was directly measured by the lock-in detection.

In the superconducting phase, a clear energy gap structure was observed in the tunneling spectra. Figure 1 shows the tunneling differential conductance as a function of the bias voltage at 1.2 K. The conduc-

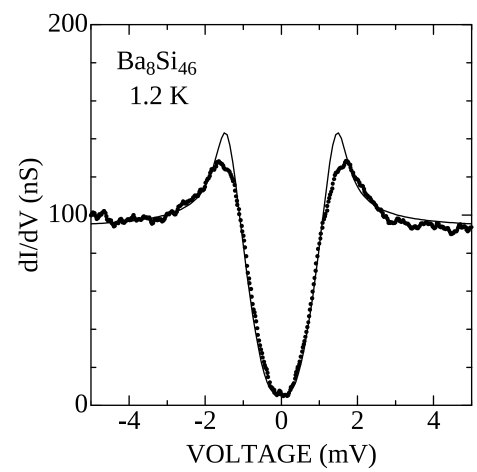

Fig. 1. The tunneling differential conductance at 1.2 K. The solid line represents the fitting by the finite gap model with Δ_{min}=0.45 meV, Δ_{max}=1.5 meV and Γ=0.045 meV.

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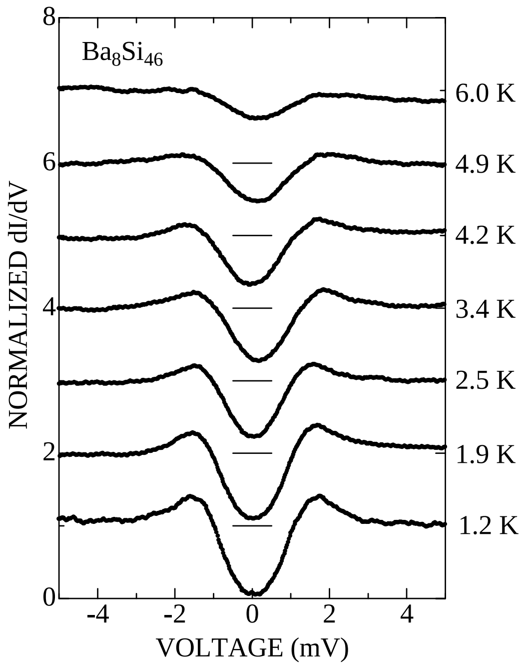

Fig. 2. Temperature dependence of the tunneling spectra. The zero conductance line of each curve is shifted by one division for clarity.

tance around zero bias voltage is well reduced and the gap edge is observed as a conductance peak at V=1.6 mV. Essentially the same conductance curve was reproduced irrespective of the tip position. We also confirmed that the tunneling spectra have no sample dependence.

The conductance curve can not be explained by the simple s-wave paring symmetry *i.e.* the isotropic gap. Finite conductance inside the gap suggests the gap anisotropy. At first, we try to fit by the d-wave symmetry with line nodes of the gap. However, the curvature of the conductance curve around zero bias voltage can not be fitted by the d-wave pairing which brings about a linear dependence on the energy. The flat conductance at zero bias voltage suggests the finite gap. Then we examine the anisotropic gap model with the finite gap [4]. In this model we assume that the gap varies from Δ_{min} to Δ_{max} depending on the direction in $\boldsymbol{k}$-space. The solid line in Fig. 1 represents the calculated curve with Δ_{min}=0.45 meV, Δ_{max}=1.5 meV and the lifetime broadening parameter [5] Γ=0.045 meV. The tunneling conductance curve is well reproduced by the model. Correspondingly, we obtained $2\Delta_{min}/\mathrm{k}T_c$=1.3 and $2\Delta_{max}/\mathrm{k}T_c$=4.4. Small value of Γ assures the validity to discuss the gap symmetry from our tunneling spectra. We conclude that the gap opens whole on the Fermi surface and varies depending on the direction in $\boldsymbol{k}$-space. We argue that the symmetry of the pair wave function is not a simple s-wave. On the other

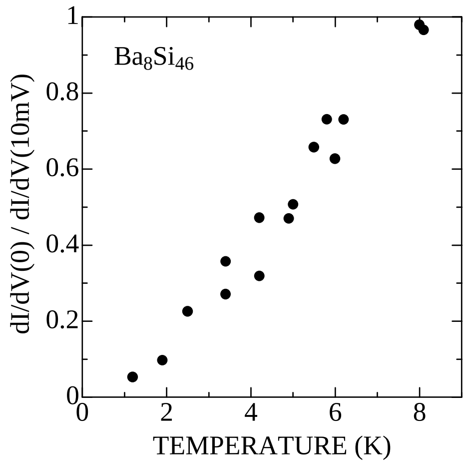

Fig. 3. Temperature dependence of the normalized zero bias conductance.

hand, Yokoya *et al.* [3] suggested the isotropic gap from the high-resolution photoemission spectra at 5.4 K. It should be pointed out that the spectra at lower temperature is essential to discuss the pairing symmetry. In order to confirm the gap anisotropy directly, we are planning to perform STS along various crystal orientations [6].

Temperature dependence of the tunneling spectra is shown in Fig. 2. The gap structure observed clearly at low temperature is found to be smeared with increasing temperature. Above T_c of 8K, the gap disappears and the conductance curve is flat indicating the metallic state. Figure 3 shows the temperature dependence of the tunneling differential conductance at zero bias voltage, which is normalized by the conductance at V=10 mV. Roughly speaking, the zero bias conductance increases almost linearly with increasing temperature. However, the number of data points is not enough to discuss the functional form in detail. We are now investigating the precise temperature dependence particularly far below T_c.

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