Electronic structure and superconducting gap of silicon clathrate Ba_8Si_{46} studied with ultrahigh-resolution photoemission spectroscopy

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(Received 20 April 2001; published 1 October 2001)

We study the electronic structure and superconducting transition of silicon clathrate Ba_8Si_{46} ($T_c=8$ K) using photoemission spectroscopy. We observe a narrow band at the Fermi level (E_F), whose width ($\sim$0.3 eV) is substantially smaller than that of band structure calculations ($\sim$1.5 eV). Ultrahigh-resolution measurements show a superconducting gap at 5.4 K [$2\Delta(0)/k_BT_c=3.51$]. Fine structures associated with phonons are observed within 70 meV of E_F. These results characterize Ba_8Si_{46} as a weak-coupling superconductor most probably driven by phonon.

DOI: 10.1103/PhysRevB.64.172504 PACS number(s): 74.25.Jb, 74.70.Wz, 79.60.−i

Silicon clathrate Na_8Si_{46} has been known as a nonsuperconducting metal down to 2 K for more than thirty years.[1] The crystal structure consists of Si_{20} and Si_{24} cages sharing their pentagonal faces with each other, with Na atoms occupying these cages (see Fig. 1). Though the silicon clathrate is reminiscent of the electron-doped C_{60}, the intercage bonding makes the clathrate different from the doped C_{60}, where individual C_{60} molecules essentially influence its physical properties: Clathrates are covalent crystals, while fullerides are molecular crystals. Motivated by the discovery of the superconductivity in the doped C_{60} compounds with the highest transition temperature (T_c) exceeding 30 K (Ref. 2) and expectation of higher T_c even in the silicon clathrates because of expected higher Debye temperatures originating in the rigid sp^3 Si-Si covalent bonding, Yamanaka *et al.* succeeded in synthesizing superconducting $Na_2Ba_6Si_{46}$ with T_c of 4 K (Ref. 3). A remarkable point of this success is that this is a superconductor with sp^3 Si-Si covalent bonding, implying a possibility of occurring superconductivity in the other cubic-silicon-like sp^3 materials. This, along with their physically and industrially interesting properties,[4–6] has brought about renewed attention, and has stimulated experimental and theoretical studies.

Comparative band structure calculations[7] of Si_{46} and $Na_2Ba_6Si_{46}$ show that the density of states (DOS) of the conduction band in $Na_2Ba_6Si_{46}$ is strongly modified compared to that of pristine Si_{46} due to strong hybridization between Si_{46} and Ba states. This modification produces a sharp peak at the Fermi level (E_F), which is thought to play a crucial role for the superconductivity because of the very high DOS at E_F. Nuclear magnetic resonance (NMR) studies have experimentally confirmed that the existence of the strong hybridization[8–10] together with partial ionization of Na and Ba in $Na_xBa_ySi_{46}$ (Ref. 8), but also discussed somewhat lower DOS at E_F compared to the value from the calculations.[7] Raman spectroscopy has been performed[11,12] and compared with calculations[13–15] in order to study the phonon modes. Recently, neutron scattering studies reported that the phonon density of states of Si_{46} is found to extend up to $\sim$70 meV (Ref. 16). However, so far, to our best knowledge, no photoemission (PE) study reporting the electronic structure of the valence band and superconducting gap of superconducting silicon clathrates is known, except for an x-ray photoemission[17] which measured the valence band of nonsuperconducting Si_{34} type clathrate samples. The reason is because bulk superconducting samples for PE measurements are not available till now. Fortunately, more recently, high-pressure synthesis enables us to make bulk Ba_8Si_{46} having T_c of 8 K (Ref. 18), giving us an opportunity to perform PE spectroscopy on this compound.

In this Brief Report, we report experimental electronic structures of Ba_8Si_{46}. The PE spectra of the valence band region show several features up to 14 eV binding energy. We also find a sharp peak at E_F, which is expected to be a crucial factor for the superconductivity from band structure

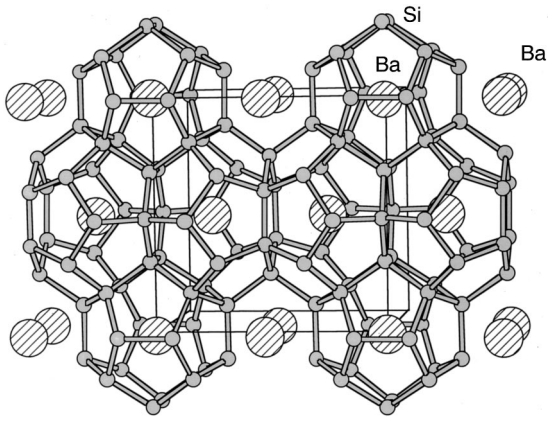

FIG. 1. Schematic structure model of Ba_8Si_{46}. Ba atoms occupy all of the silicon cages.

calculations.[7,19] But the observed bandwidth (~0.3 eV) of the peak at E_F is narrower than the calculated bandwidth (~1.5 eV), suggestive of a deviation from one electron approximation. Furthermore, we observe a clear opening of a superconducting gap below T_c with the gap size of 1.3 meV, which corresponds to a reduced gap size of $2\Delta(0)/k_BT_c = 3.51$. We also observe fine structures up to ~70 meV in superconducting spectrum, whose energy is nearly equivalent to the highest phonon energy for Na_8Si_{46} clathrate.[16] These results for the superconducting state classify Ba_8Si_{40} into a weak-coupling superconductor most probably mediated by phonon. These experimental results provide direct information on the electronic structure and superconducting transition of the silicon clathrate superconductor.

Ba_8Si_{46} samples were prepared using a high-pressure synthesis as described in the literature.[18] Ba_8Si_{46} made by the same procedure has shown superconductivity below 8 K for both resistivity and susceptibility measurements.[18]

PE measurements were performed on a spectrometer built using a GAMMADATA-SCIENTA SES2002 electron analyzer and a high-flux discharging lamp with a toroidal grating monochromator. The total energy resolutions (analyzer and light) for total valence band measurements using the He Iα (21.218 eV) and He IIα (40.814 eV) resonance lines were set to 70 and 100 meV, respectively, while that for E_F region was set to 8 meV. Ultrahigh-resolution measurement very close to E_F for a superconducting gap was done with 2.4 meV resolution. The sample temperatures were measured using a silicon-diode sensor mounted just close to it. The base pressure of the spectrometer was better than 5×10^{-11} Torr. Samples were fractured *in situ* to obtain clean surfaces and all the measurements were done within 3 h after the fractures. We did not see any spectral changes within the time interval, indicating the observed spectra are reflecting intrinsic electronic structures. Temperature dependent spectral changes were confirmed by cycling temperature across T_c. E_F of samples was referenced to that of a gold film evaporated onto the sample substrate and its accuracy is estimated to be better than ± 0.05 meV.

Figure 2 shows valence band PE spectra of superconducting Ba_8Si_{46} obtained at 5.4 K using He Iα and He IIα. The valence band spectrum measured with He II α shows a peak at E_F and several features as shown by vertical lines. Corresponding structures are seen in He Iα spectrum, though the accessible energy region of He Iα spectrum is smaller than that of He IIα due to the smaller photon energy. In Fig. 2, we also show the total DOS obtained from the first principals calculations using local density approximation (LDA) (Ref. 19), incorporating a matrix element effect as well as resolution and lifetime broadening as a Gaussian with full width at half maximum (FWHM) of 0.5 eV. As shown with thin dotted lines, the experimentally observed features beyond 2 eV can be related to those in the calculated DOS. However, well-separated three prominent structures which can be assigned to Si 3*s*, Si 3*s*-*p*, and Si 3*p* like states of the Si_{46} framework in the calculations do not clearly appear in the experimental spectrum. This indicates that the Ba atom influences the Si_{46} cage more than the expectation from band

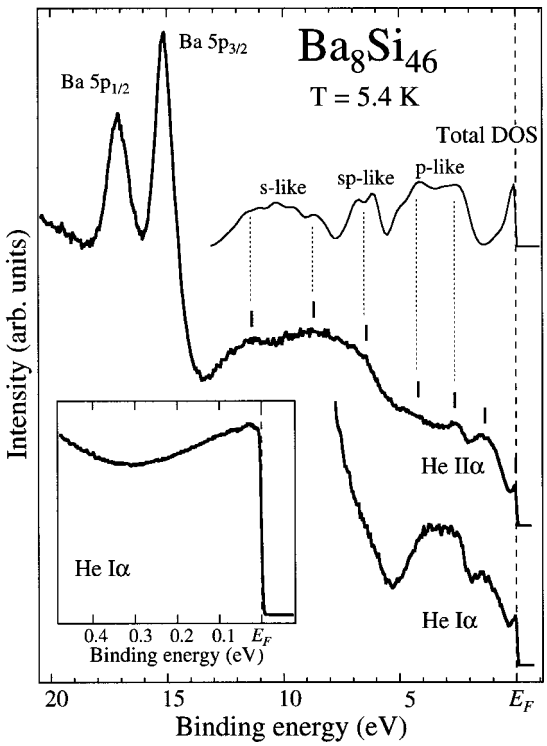

FIG. 2. Valence band PE spectra of Ba_8Si_{46} measured He Iα and He IIα resonance lines at 5.4 K (thick lines), together with the total DOS calculated by first principle LDA calculations (Ref. 19) including matrix element effects and broadened with a Gaussian with FWHM of 0.5 eV (thin line). The inset shows high-resolution (8 meV) spectra near E_F of Ba_8Si_{46}.

calculations, supporting the NMR study which confirmed the existence of strong hybridization in $Na_xBa_ySi_{46}$.[8]

Furthermore, we find there is a substantial discrepancy between the present results and calculations especially for the electronic states within 2 eV below E_F. Besides a peak at E_F, we observe a broad hump at 1.5 eV in the observed spectrum, no representative structure of which we see in the calculation. The observed result is reminiscent of that reported for metal-insulator transition systems like V_2O_3.[20] As for the peak at E_F, the intensity seems smaller compared to the intensity of the bands at 2–6 eV, while those are similar in the calculation. Further, the width of the peak at E_F is smaller than that of the calculated one, as shown in the inset of Fig. 2. We see that the peak shows a width of ~0.3 eV with fine structures near E_F (we will discuss this later), while the calculated peak has a width of ~1.5 eV. These results indicate that the LDA calculation is not enough for describing the electronic structure of Si clathrate, implying importance of electron correlations which may be expected from the flat bands due to its large unit cell, as in the C_{60} crystals.[2] However, in order to address the electron correlation in the silicon clathrates, further studies including resistivity, specific heat, and de Haas–van Alphen measurements will be necessary.

In He IIα spectrum, we can observe Ba $5p_{1/2}$ and $5p_{3/2}$ shallow core levels at 17.1 and 15.1 eV binding energies, respectively. The energy position of the Ba $5p_{3/2}$ is 15.1 eV

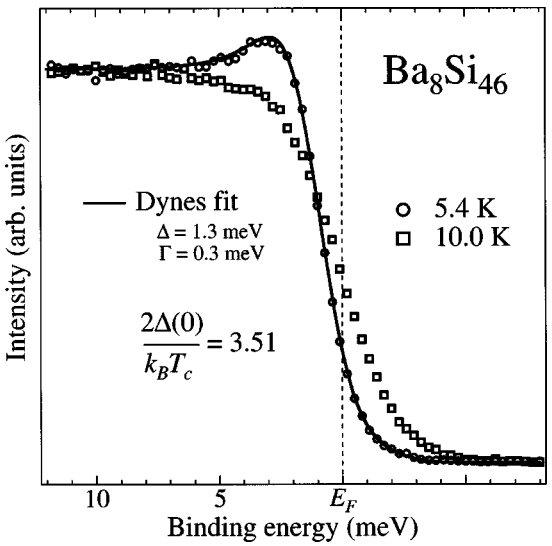

FIG. 3. Ultrahigh-resolution PE spectra of Ba_8Si_{46} measured at 5.4 K (superconducting state, open circles) and 10.0 K (normal state, open squares) using an energy resolution of 2.4 meV. A curve superimposed on the superconducting spectrum is the result of a numerical calculation using the Dynes function with $\Delta=1.3$ meV and $\Gamma=0.3$ meV.

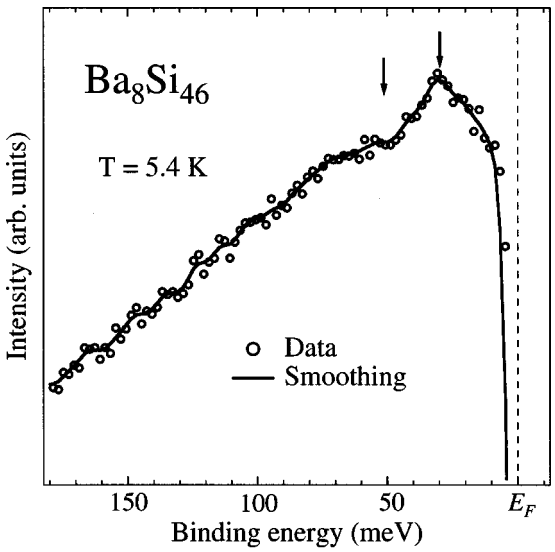

FIG. 4. High-resolution PE spectrum of Ba_8Si_{46} using an energy resolution of 8 meV (open circles) together with a smoothing curve demonstrating existence of fine structures. Arrows are representing the positions of a weak dip (~50 meV) and a maximum (~30 meV) in the intensity.

and found to have a shift of 0.6 eV compared to that of a Ba metal (14.6 eV) (Ref. 21). This value is similar to the shift of $5p_{3/2}$ reported for BaS (0.53 eV) but slightly smaller than that of BaO (0.86 eV) (Ref. 22), in which Ba atoms are believed to take a divalent state. This observation agrees with the NMR measurements[8] reporting that the Ba atoms are partially ionized, indicating a covalent-like bonding of Ba atoms and Si_{46} cages.

To study the superconducting electronic structure of Ba_8Si_{46}, we further performed ultrahigh-resolution measurements. In Fig. 3, we show the results measured at 5.4 K (superconducting state, open circles) and 10.0 K (normal state, open squares) normalized with area under the curve from 12 to -8 meV. The normal state spectrum has a leading edge whose midpoint is nearly located at E_F. In contrast, the superconducting-state spectrum exhibits a spectacular redistribution of the spectral intensity from at and above E_F to higher binding energy, forming a new peak around 3 meV. This is a direct measurement of the superconducting gap of silicon clathrates. To obtain the magnitude of the superconducting gap, we have done numerical simulations using the Dynes function,[23] assuming a constant normal-state DOS and using the energy resolution of 2.4 meV. We superimpose a result using $\Delta=1.3\,\mathrm{meV}$ and $\Gamma=0.3\,\mathrm{meV}$ (curve), which well reproduces the superconducting spectrum as shown in Fig. 3. From the known temperature dependence of the superconducting gap for both weak- and strong-coupling superconductors,[24] we estimate the gap value at 0 K and obtain a reduced gap, $2\Delta(0)/k_BT_c=3.51$. This classifies Ba_8Si_{46} into a weak-coupling superconductor. We note that this value is similar to those obtained for K_3C_{60} and Rb_3C_{60} (3.53) using photoemission spectroscopy.[25]

Lastly, we turn to the structures near E_F but in slightly wider regions as shown in Fig. 4. First we emphasize that the spectrum is for the superconducting state, though it does not show the superconducting condensation peak due to a lower resolution (8 meV) and a larger step size (2 meV) compared to the energy scale of the superconducting gap. As one can see, the intensity has a maximum at 30 meV and broad shoulder around 70 meV. Consequently, we observe a weak dip around 50 meV and intensity suppression close to E_F. We find that the energy positions of the dip and the maximum relate very well to the peak and dip positions in the phonon spectrum of Na_8Si_{46} (Ref. 16), respectively, indicating that the electrons are coupled with phonons in the superconducting state. We observe similar spectral shape even for normal state, consistent to the Raman scattering measurement reporting importance of electron-phonon coupling for the normal state.[11] These results suggest the superconductivity of silicon clathrate is most probably driven by phonon.

In conclusion, we have studied the electronic structure and superconducting transition of the silicon clathrate superconductor, Ba_8Si_{46}, using PE spectroscopy. We observed a peak at E_F for superconducting Ba_8Si_{46}, suggesting that the peak at E_F is a necessary feature to get superconductivity for this different type of superconductor. From the ultrahigh-resolution PE spectroscopy, we observe a reduced gap of 3.51 as well as phonon-induced features. These indicate the superconductivity of the silicon clathrate classified as a weak-coupling one most probably mediated by phonon. These experimental results provide important information on the electronic structure and the mechanism for this superconductor with the unique structure.

We would like to thank Dr. A. Chainani for valuable and stimulating discussion. This work was supported by grants from the Ministry of Education, Culture and Science of Japan. T.K. thanks JSPS for financial support.

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Erratum: Electronic structure and superconducting gap of silicon clathrate Ba_8Si_{46} studied with ultrahigh-resolution photoemission spectroscopy [Phys. Rev. B 64, 172504 (2001)]

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(Received 15 June 2004; published 20 October 2004)

DOI: 10.1103/PhysRevB.70.159902 PACS number(s): 74.25.Jb, 74.70.Wz, 79.60.−i, 99.10.Cd

The reduced gap value of $2\Delta(0)/k_BT_c$ referred to in this paper (3.51) is incorrect. The correct value is 4.38. Accordingly, electron-phonon coupling of Ba_8Si_{46} is rather strong, and larger than those obtained for K_3C_{60} and Rb_3C_{60} (3.53) using photoemission spectroscopy.

