Twofold symmetry of proximity-induced superconductivity on Bi$_2$Te$_3$/Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ heterostructures revealed by scanning tunneling microscopy

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We observe proximity-induced superconductivity on the heterostructures constructed by topological insulator Bi$_2$Te$_3$ thin films and high-temperature cuprate superconductors Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212). It is found that gap anisotropy is required to fit the tunneling spectra measured on the Bi$_2$Te$_3$ thin films with thickness of 2 quintuple layers (QLs), and the gap maximum is about 7.6 meV. The superconducting gap increases with increase of the film thickness. Spatial mappings of the density of states, namely the quasiparticle interference (QPI) patterns are also measured at different energies. The Fourier transformed (FT-) QPI patterns measured on the 2QL Bi$_2$Te$_3$/Bi2212 heterostructures at energies above the superconducting gap reveal a hexagonal shape with the scattering spots along the ΓM directions. This is consistent with the scattering process of the topological surface states considering the forbidden backscattering rules. FT-QPI patterns with twofold symmetry are observed at low energies near the Fermi level on the 2QL heterostructures, which suggests a twofold anisotropic superconducting gap with gap minima along one pair of the principal crystalline axes of Bi$_2$Te$_3$. This gap form is consistent with the Δ$_{4y}$ notation of the topological superconductivity proposed in such systems. Our results provide fruitful information of the possible topological superconductivity induced by proximity effect on high temperature superconducting cuprates.

Subject Areas: Condensed Matter Physics, Superconductivity, Topological Insulators

I. INTRODUCTION

Topological superconductors (TSCs) with the pairing symmetry of odd parity host the Majorana bound states or Majorana zero modes which may play an important role in the future application of topological quantum computation [1, 2]. A variety of approaches have been applied to achieve topological superconductivity after the initial theoretical predictions of topological nature in 2D $p + ip$-wave [3] and 1D $p$-wave superconductors [4]. One widely adopted method to obtain topological superconductivity is to dope the topological insulators (TIs), for example, M$_x$Bi$_2$Se$_3$ (M = Cu, Sr, or Nb) [5, 8], the resultant superconductors have various properties related to the time-reversal-invariant topological superconducting states [9, 12]. Theoretically, some iron-based superconductors are also predicted as the possible candidates of the TSCs [15, 18], and experimentally the Dirac-cone-type spin-helical surface states [10, 21] as well as the vortex cores with possible Majorana zero modes [20, 22] are observed, which serve as the possible evidence of topological superconductivity in these iron-based materials. Another approach to realize TSC is to construct the TI/superconductor heterostructures, and the superconductivity on the TI layer induced by proximity effect may be topological nontrivial [23]. Such kind of superconductivity is successfully realized and proved on TI films grown on superconducting substrates of 2H-NbSe$_2$ [24–26] and FeTe$_{0.53}$Se$_{0.45}$ [27, 28]. Cuprates keep the highest superconducting critical temperature ($T_c$) record at atmosphere pressure, and the very large superconducting gap makes them a good candidate to induce proximity-induced superconductivity on the topological films made on top of them. According to the theoretical predictions, the proximity effect may even be enhanced by the mismatch of the TI film and the cuprate Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212) substrate [29, 30]. By now, several attempts have been made on TI/Bi2212 heterostructures [31–34]. A superconducting gap was observed on the TI layer in some measurements [31, 32], however, these works were challenged and questioned by other works due to the absence of the superconducting gaps in the latter measurements [33, 34].

For the TSCs with $D_{3d}$ crystalline symmetry, a twofold anisotropic superconducting gap seems to be a common feature due to the $d$-vector of an odd-parity gap. This twofold symmetric gap is observed in M$_x$Bi$_2$Se$_3$ materials from different kinds of measurements [35, 38], and such gap breaks the threefold rotational symmetry of the crystal structures in these materials. The feature is explained as the spin-orbit interaction associated with the hexagonal warping effect which can induce a fully gapped superconducting gap with odd parity [39]. The twofold symmetric nodeless superconducting gap is also observed on 2QL Bi$_2$Te$_3$/FeTe$_{0.53}$Se$_{0.45}$ heterostructures determined from twofold symmetric in-gap quasiparticle interference (QPI) patterns and elongated vortices [27], and the obtained gap function is consistent with the $\Delta_{4y}$ gap notation predicted theoretically for TSCs in the related studies [39].

Here we report the successful deposition of the TI Bi$_2$Te$_3$ thin films on Bi2212. We observe the proximity-induced superconductivity on the surface of
the heterostructures of Bi$_2$Te$_3$/Bi2212 by scanning tunneling microscopy/spectroscopy (STM/STS) measurements. A twofold symmetric superconducting gap is inferred from the twofold symmetric Fourier-transformed (FT-) QPI patterns at low energies near the Fermi level on the heterostructures with different Bi$_2$Te$_3$ thicknesses. Our observations provide evidence of topological nature of proximity-induced superconductivity on the Bi$_2$Te$_3$/Bi2212 heterostructures.

II. EXPERIMENTAL METHOD

The optimally doped Bi2212 single crystals were grown by the floating-zone technique [40]. The superconducting transition temperature $T_c$ is about 90 K for Bi2212 samples as determined through the magnetization measurements with a SQUID-VSM (Quantum Design). The single crystals were cleaved in ultrahigh vacuum at room temperature, and the obtained top surface was a fresh BiO layer. Before the growth of the Bi$_2$Te$_3$ films, the Bi2212 substrate was heated to 540 K to degas in the molecular beam epitaxy (MBE) chamber. The Bi$_2$Te$_3$ thin films were grown layer by layer on the cleaved Bi2212 substrate by using MBE technique [41]. The flux ratio of Bi and Te was about 1:10 during the growth, and the film growth rate was about 0.14 QL/min. The progress of the film growth was monitored by the reflection high-energy electron diffraction. STM/STS measurements were carried out in a scanning tunneling microscope (USM-1300, Unisoku Co., Ltd.) with the ultrahigh vacuum, low-temperature, and magnetic field up to 11 T. The electrochemically etched tungsten tips were used during all the measurements. A typical lock-in technique was used with an ac modulation of 0.4 mV and 987.5 Hz. All the STM/STS data in this paper were taken at 1.5 K.

III. RESULTS

A. Tunneling spectra and superconducting gaps on Bi$_2$Te$_3$/Bi2212 heterostructures

Figure 1(a) shows the atomically resolved topography of Bi2212 after cleavage before the film growth. One can see that the top BiO surface is constructed by a square lattice with the lattice constant of about 3.8 Å, and the supermodulations which are common for the Bi2212 system are widely spread on the surface. The Bi$_2$Te$_3$ thin films are then successfully grown on the cleaved surface of Bi2212, and we show a typical atomically flat Bi$_2$Te$_3$ surface in Fig. 1(b). The top atom layer of the film is consisted by Te atoms, and it has the hexagonal lattice structure with the lattice constant of about 4.3 Å. The perfect hexagonal lattice can also be verified by the sharp and sixfold symmetric Bragg spots shown in the FT image as the inset of Fig. 1(b). When we do the scanning in a relatively large area, we can observe some neig-

![Image 1](http://example.com/image1.png)

**Fig. 1.** (a) Typical atomically resolved topography of the top BiO surface of the optimally doped Bi2212 sample. Set-point conditions are $V_{set} = 100$ mV, $I_{set} = 50$ pA. (b) Atomically resolved topographic image of the 2QL Bi$_2$Te$_3$ thin film grown on the top surface of Bi2212 ($V_{set} = 50$ mV, $I_{set} = 50$ pA). The inset shows the FT image of the topography, and one can see six sharp Bragg peaks with almost the same intensities. (c) Topography of Bi$_2$Te$_3$ film with different thicknesses in a large area with the dimensions of $80 \times 24$ nm$^2$ measured with set-point $V_{set} = 250$ mV and $I_{set} = 50$ pA. (d) Spatial distribution of height measured along the arrowed line in (c). (e) A series of differential conductance spectra measured on the heterostructures with different thicknesses of Bi$_2$Te$_3$ layer ($V_{set} = 0$ mV, $I_{set} = 100$ pA). The spectra are offset vertically for clarity. The arrows point out the characteristic energies of the kinks probably arising from the Dirac points of the surface states.
upper panels that the films are flat and homogeneous in such large areas. And the tunneling spectra are roughly homogeneous when the measurement go along the arrowed lines with the lengths of about 28 nm. The uniformity of the spectra across certain areas indicate that the Bi$_2$Te$_3$ films are homogeneous with high quality. Superconducting gapped features can be observed on the spectra near zero bias even when the film is as thick as 5 QL (about 5 nm). However, the zero-bias conductance increases with increase of film thickness. The superconducting gaps, which can be estimated from the energy difference between two coherence peaks, are also spatially uniform along such a long distance. Therefore, we conclude that superconductivity is successfully induced on the Bi$_2$Te$_3$ films due to the proximity effect of the cuprate superconductor Bi$_2$2212.

Figure 3(a) shows some typical tunneling spectra measured on the Bi2212 single crystal and the Bi$_2$Te$_3$/Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ heterostructures. One can see that with increase of film thickness, the zero-bias conductance increases continuously, while the gap values decreases steadily. The latter is determined by the energy difference between two coherence peaks. Because of the relatively large zero-bias differential conductance, the exact value of superconducting gap should be obtained from the fitting procedures. Then we use the Dynes model [42] with a single gap to fit the measured tunneling spectra. For the spectrum measured on Bi2212, we use a $d$-wave gap function to fit the experimental data. The obtained gap value 43 meV is in the statistical gap range obtained from our previous report [43]. For the spectrum measured on 2 QL heterostructures with relatively high zero-bias conductance, the Dynes model with an isotropic $s$-wave gap cannot fit the spectrum well, hence the gap should be anisotropic on the heterostructures. We observed a twofold symmetric superconducting gap on Bi$_2$Te$_3$/FeTe$_{0.55}$Se$_{0.45}$ heterostructures from our previous work [27], which is consistent with a fully gapped $\Delta_{ly}$ notation predicted for TSC [39]. From a theoretical prediction for the TI/$d$-wave-cuprate heterostructure [29], the possible paring gap is also nodeless and twofold symmetric. In addition, as shown by the twofold symmetric FT-QPI data presented below, it is likely that the gap function is also a twofold symmetric one on the Bi$_2$Te$_3$/Bi2212 heterostructures. Then we use a twofold symmetric gap to fit the spectra measured on the heterostructures. The general gap function reads $\Delta = \Delta_{max} [(1 - x) \cos 2\theta + x]$ with $\Delta_{max}$ the gap maximum and $x$ the gap anisotropy. When $x = 0$, the gap is a standard $d$-wave one; when $0.5 < x < 1$, it is a twofold symmetric but nodeless $s$-wave gap. From the fitting procedures, it is impossible to determine whether there are gap nodes on the gap function for the spectra measured on Bi$_2$Te$_3$/Bi2212 heterostructures, because the Dynes...
models with a pure $d$-wave and an anisotropic $s$-wave gap can both fit the data well. However, the value $\Delta_{\text{max}}$ is almost independent of the gap function from the fittings. For the spectrum measured on the 2 QL heterostructure, $\Delta_{\text{max}}$ is about 7.5 meV for a $d$-wave gap; by using an anisotropic $s$-wave gap with $x$ between 0.65 to 0.7 and the corresponding $\Delta_{\text{max}}$ from 7.7 to 7.65 meV, the spectrum can also be well fitted. So $\Delta_{\text{max}}$ values as determined from either the anisotropic $s$-wave or the $d$-wave gap are all in the range of 7.6 ± 0.2 meV for the 2 QL film. In this point of view, the gap function seems to have a negligible influence on the $\Delta_{\text{max}}$. In Fig. 3(a), we show some typical fitting results to the spectra measured on the heterostructures by using the anisotropic $s$-wave gap, and the gap maximum values are shown in Fig. 3(b). The error bars are determined from the trying to have the best fitting when adjusting the parameters $x$ and broadening factor $\Gamma$ in the Dynes model fitting procedures. One can see that $\Delta_{\text{max}}$ decreases with increase of the thickness of the Bi$_2$Te$_3$ layers, which follows approximately an exponential decay law. Similar results were observed in the TI/2H-NbSe$_2$ heterostructures [24, 25]. As shown in Fig. 3(a), the linear extension value $\Delta_{\text{max}}$ (0 QL) = 13.5 meV is smaller than the gap maximum of Bi2212, which may be understood in the theoretical framework of proximity-induced superconductivity [14].

B. Normal-state FT-QPI results

The QPI images, which are the differential conductance mappings from STM measurements, contain spatial periodic variations of local density of states (LDOS) in real space due to impurity scattering on the surface of a metal. After doing Fourier transformation to the QPI image, one can get the FT-QPI images which contain the scattering information in $q$-space. The process can be reinterpreted as the elastic scattering in momentum space between two segments with momentum difference of $\Delta k$ at some energies, and such scattering can result in the characteristic scattering spot with a vector of $q = \Delta k$ from the origin point of FT-QPI image [45]. However, this analysis is based on the spin-independent scattering matrix, and it is consequently not suitable for analyzing the FT-QPI patterns from the topological surface states. The scattering probability should strongly depend on the spin configurations of the surface states in TIs, e.g., the backscattering induced by nonmagnetic impurities is absent in TI material Bi$_{0.92}$Sb$_{0.08}$ because of the chiral spin texture of the material [46]. However, some characteristic scattering spots from the surface states are observed on Bi$_2$Te$_3$ films [47], which is interpreted as the contributions from the off-plane spin orientations [48, 49] when considering the hexagonal warping effect [50]. We have also done the QPI measurements in an area of a 2QL Bi$_2$Te$_3$/Bi2212 heterostructure with the corresponding topography shown in Fig. 3(b). Figure 3(a) shows the obtained normal-state QPI image measured at +20 mV which is much larger than the superconducting gap, and one can see clear periodic standing waves on the surface. In FT-QPI pattern shown in Fig. 3(b), one can see six clear spots along $\Gamma M$ directions instead of continuously distributed pattern from a complete Fermi surface, and the intensities of the six spots are almost the same along different $\Gamma M$ directions. The FT-QPI results obtained on the 2QL Bi$_2$Te$_3$/Bi2212 heterostructures are similar to the results measured on Bi$_2$Te$_3$ films grown on Si substrates [17]. Figure 4(c) shows a schematic image of two-dimensional Fermi surface of the topological surface states in Bi$_2$Te$_3$ based on the angle-resolved photoemission spectroscopy (ARPES) results near the Fermi energy $E_F$. The density of states (DOS) is large on the belly parts of the Fermi surface along $\Gamma K$ directions, while that is small on the sharp corners of the Fermi surface along $\Gamma M$ directions. When we do the self-correlation to the Fermi surface, we can obtain the simulated FT-QPI patterns shown on the left half part in Fig. 4(d) without considering any spin selection rules. There are three kinds of main characteristic scattering patterns in the simulated FT-QPI image, i.e., with the scattering vectors of $q_1$, $q_2$, and $q_3$. However, the scatterings with vectors of $q_1$ and $q_3$ are forbidden since the off-plane spin direc-

\[ \text{FIG. 4. (a) QPI image measured at +20 mV on the 2 QL Bi$_2$Te$_3$/Bi2212 heterostructure with the corresponding topography shown in Fig. 3(b)} \ (V_{\text{set}} = +30 \text{ mV}, I_{\text{set}} = 100 \text{ pA}). \] \[ \text{One can see clear electronic standing waves on the surface. (b) FT-QPI pattern based on the QPI data in (a). The bias voltage +20 mV is much larger than the superconducting gap, and the FT-QPI pattern is the result of scattering between the segments of Fermi surface in normal state. (c) Schematic plot of the snowflake-like Fermi surface of the surface state in Bi$_2$Te$_3$. (d) Simulated FT-QPI pattern by doing self-correlation to (c) without (left half part) and with (right half part) considering the spin selection rules.} \]
spots with scattering vectors of $\mathbf{q}_2$. That explains why we only see the scattering spots with scattering vectors of $\mathbf{q}_2$ in our measurements, as illustrated in the right half part of Fig. 4(d).

It should be noted that, in our previous studies we found that the scattering spots are in the $\Gamma K$ directions for the FT-QPI patterns measured on the 2QL Bi$_2$Te$_3$/FeTe$_{0.55}$Se$_{0.45}$ heterostructures at about ±4 meV. Since the magnitude of 4 meV is beyond the superconducting gap, what measured reflects actually the FT-QPI pattern of the normal state. This result seems to be different from the scattering spots along $\Gamma M$ directions from most of the reported results and also the result here measured on 2QL Bi$_2$Te$_3$/Bi-2212 heterostructures. From a recent report, we notice that the scattering spots are along $\Gamma M$ directions when measured at a high energy of +50 mV on the 3QL Bi$_2$Te$_3$/FeTe$_{0.55}$Se$_{0.45}$ heterostructures. A similar result is observed in Bi$_2$-Fe$_{1-x}$Te$_{3+4d}$, and the scattering spots change from $\Gamma M$ to $\Gamma K$ directions when decreasing the measuring energy; the authors attribute this crossover to the magnetic Fe impurities which break the time-reversal symmetry. In previous ARPES measurements, it was found that with increase of energy from the Dirac-point, the topology of the surface states changes from the anisotropic hexagon type to snowflake like, and the direction of the maximum DOS intensity on the Fermi surface changes from $\Gamma M$ to $\Gamma K$. The possible reason for the scattering spots along the $\Gamma K$ direction in the 2QL Bi$_2$Te$_3$/FeTe$_{0.55}$Se$_{0.45}$ heterostructures may be due to relatively small energy difference between the Fermi energy and the Dirac-point, which is different from the case in the present 2QL Bi$_2$Te$_3$/Bi-2212 heterostructures. For a comparison, we carry out a rough estimation of the hexagonal area enclosed by the scattering spots of the FT-QPI patterns in the two systems, and the area in the 2QL Bi$_2$Te$_3$/Bi2212 heterostructure is about 20% larger than that measured on the 2QL Bi$_2$Te$_3$/FeTe$_{0.55}$Se$_{0.45}$ heterostructure. Thus the fact that the scattering spots along the $\Gamma M$ direction in the present system of 2QL Bi$_2$Te$_3$/Bi2212 heterostructures are consistent with most of the previous results, indicating a relatively larger distance of the Fermi energy from the Dirac cone.

C. Twofold superconducting gap determined from QPI measurements

The superconducting gap anisotropy can also be obtained from the QPI measurements. In order to get the detailed information of the superconducting gap on the heterostructures, we measure the QPI images at different energies on the 2QL Bi$_2$Te$_3$ films (not shown here) and show the corresponding FT-QPI patterns in Fig. 5(a)-(f). From our previous FT-QPI results measured on 2QL Bi$_2$Te$_3$/FeTe$_{0.55}$Se$_{0.45}$ heterostructures, there are no obvious scattering spots observed at zero bias, and we argue that the superconducting gap is nodeless for the proximity-induced superconductivity on the Bi$_2$Te$_3$ film. In contrast here on the 2QL Bi$_2$Te$_3$/Bi2212 heterostructure, one can see that four characteristic scattering spots appear even at zero bias from Fig. 5(a) although the intensity of these spots is very weak when compared with that of spots measured in normal state [e.g. as shown in Fig. 5(f)]. However,
this does not mean that the gap should be nodal, and may suggest that the gap minimum is quite small. At low energies of 0 and 2 meV, one can see that a couple of scattering spots along one pair of ΓM directions has very weak intensities when compared with the spots in the same area on normal-state FT-QPI pattern measured at +12 meV. Although the pair of spots along one of the ΓM directions is very weak or invisible below the energies of about 6 meV, they become however much clear at higher energies, for example as shown in Fig. 5(c) and 5(f) at energies of 8 and 12 meV respectively. They have almost the same intensity as those of other scattering spots along the ΓM directions at 8 meV near the superconducting gap maximum. The relatively weak intensity of the scattering spots along ΓM directions at low energies suggest the gap maximum in this direction. To further strengthen our argument, we try to simulate the FT-QPI pattern in the presence of a twofold anisotropic s-wave gap. First we adopt the Fermi surface of the system which has a sixfold symmetry as shown in Fig. 4(c), then we multiply the intensity of each k-point by a factor of \( \sin^2 \theta \) with \( \theta \) the angle beginning from the vertical ΓM direction, and the final angular dependent intensity is shown as the color plot of the outer contour in Fig. 5(g). One can see clearly the twofold symmetric DOS distribution along the Fermi surface, namely the intensities are very weak for the two segments of Fermi surface near the gap-maximum ΓM directions. However, we must emphasize that this serves only as a qualitative description. By doing self-correlation to Fig. 5(g) and considering the spin selection rules, we obtain the simulated FT-QPI pattern and show it in Fig. 5(h). A pair of scattering spots along one of the ΓM directions is very weak, which agrees well with the experimental data. Hence, we conclude that the gap maxima are along ΓM directions and the gap minima are along one pair of the principal crystalline axes or the ΓK directions. It should be noted that the gap minima directions on the 2QL Bi\(_2\)Te\(_3\)/Bi2212 heterostructures are the same as those on the 2QL Bi\(_2\)Te\(_3\)/FeTe\(_0.55\)Se\(_0.45\) heterostructures \([27]\), although the characteristic scattering spots are along different directions when they are measured outside the gap energy.

In order to illustrate the QPI intensity variation more clearly, we integrate the FT-QPI intensity for each angle \( \theta \) by summing all the data points between the two circles as illustrated in Fig. 5(a) and in the angle range of \( \theta \pm 5^\circ \). The obtained integrated intensity curves are shown in Fig. 6(a) for the data measured at zero bias for the two segments of Fermi surface near the gap-maximum ΓM directions. We also investigate the angle dependence of the integrated intensity of the scattering spots plotted in polar coordinates, and the data are measured on heterostructures with different thicknesses of Bi\(_2\)Te\(_3\) but all at \( E = +2 \) meV. The angle range for integration is \( \pm 5^\circ \) for each angle value. The integral background intensities are also plotted as the dotted lines by using the same color as the corresponding integral curve in this figure; they are taken far away from any characteristic scattering spots and with the same number of data points as the corresponding integral curve. Both the experimental integrated curves and the background dotted lines are shifted for clarification.

**FIG. 6.** (a) Angle dependence of integrated FT-QPI intensity plotted in polar coordinates obtained on 2QL Bi\(_2\)Te\(_3\)/Bi2212 heterostructures. The data are measured at negative energies on the same area as those measured for the FT-QPI patterns shown in Fig. 5(a)-5(f). The integrated FT-QPI intensity for each angle \( \theta \) is calculated by summing all the data points between the two dotted circles and in the angle range of \( \theta \pm 5^\circ \). (b) Angle dependence of integrated intensity of the scattering spots plotted in polar coordinates, and the data are measured on heterostructures with different thicknesses of Bi\(_2\)Te\(_3\) but all at \( E = +2 \) meV. The angle range for integration is \( \pm 5^\circ \) for each angle value. The integral background intensities are also plotted as the dotted lines by using the same color as the corresponding integral curve in this figure; they are taken far away from any characteristic scattering spots and with the same number of data points as the corresponding integral curve. Both the experimental integrated curves and the background dotted lines are shifted for clarification.
sured on the 5QL heterostructure, some weak anisotropy can still be observed. The weakening of anisotropy on the heterostructures with thicker Bi$_2$Te$_3$ films is understandable since the differential conductance increases rapidly within the gap as shown in Fig. 3(a). Therefore, the twofold symmetric superconducting gap with gap maxima along one pair of ΓM directions can be observed on the Bi$_2$Te$_3$/Bi2212 heterostructures, this conclusion is reached by the observation of the clear twofold symmetric FT-QPI patterns at some energies within the gap maximum.

**IV. DISCUSSION**

It is worth stressing that we observe the proximity-induced superconductivity on the Bi$_2$Te$_3$/Bi2212 heterostructures from the tunneling spectra and QPI results, and the superconducting gap maximum for 2QL heterostructures is found to be 7.6 ± 0.2 meV based on the fittings to the measured tunneling spectra. The gap value is similar to the one of 6 meV determined from the Andreev reflection spectra measured on Bi$_2$Se$_3$/Bi2212 junctions fabricated by mechanical bonding technique [31]; the authors obtained a gap value of about 13 meV on Bi$_2$Se$_3$/Bi2212 junctions [31]. Similar gap value of 15 meV is observed by ARPES measurements on Bi$_2$Se$_3$/Bi2212 heterostructures with Bi$_2$Se$_3$ thickness of 7 QLs [32]. However, the superconducting gap has not been measured on the same kind of heterostructures in the following ARPES measurements even when the Bi$_2$Se$_3$ film is as thin as 1-2 QLs [33, 34], and the authors argue that one possible reason for this is because of the very short coherence length of Bi2212 along c-axis. In the current work, we observe clear superconducting gapped feature from tunneling spectra as shown in Fig. 3(a), and the gapped feature exists on the Bi$_2$Te$_3$/Bi2212 heterostructures with thickness of more than 5 nm (5 QLs). In contrast, the coherence length values of Bi2212 single crystals are about ξ$_{ab}$ = 0.38 nm and ξ$_c$ = 0.16 nm in zero-temperature limit [55], and this value is much smaller than the effective range (more than 5 nm) where superconductivity can be detected in Bi$_2$Te$_3$. Similarly on Bi$_2$Te$_3$/NbSe$_2$ heterostructures, the superconducting gapped feature remains when the thickness of Bi$_2$Te$_3$ is more than 11 nm (11 QLs) [25], although the coherence length values of NbSe$_2$ are ξ$_{ab}$ = 7.7 nm and ξ$_c$ = 2.3 nm in zero-temperature limit [56]. It should be noted that for the proximity-induced superconductivity from a conventional superconductor to a closely contacted metal, the superconducting effective range in the normal metal has no clear relationship to the coherence length of the superconductor, but is in the scale of $\sqrt{\hbar D_n/2\pi k_B T}$ with $D_n$ the diffusion coefficient which is proportional to the Fermi velocity $v_F$ and the mean free path $l_c$ of the normal metal [44]. Thus the effective length of superconductivity in the metal can be much larger than the coherence length of the superconductor. Besides, the presence or absence of proximity-induced superconductivity is also strongly related to the perfectness of the interface [44]. For example, if the metallic film is granular with grain boundaries, the proximity-induced superconductivity is also related to the grain boundary density [55]. For the proximity effect in heterostructures with copper oxide as the substrate, such as Bi2212 used here, because superconductivity of the top layer in the cuprate is very sensitive to the annealing condition and the c-axis coherence length is very short, both can easily induce a degraded order parameter on the top layer. This may be the reason for different results coming out of different groups. For many measurements in the area with 2QL thickness, the nominal deposition thickness is of 3QLs, thus the thickness of the film is actually not uniform. For ARPES measurements, since the photon spot is quite large, one detects probably the signal from areas with different thickness. Since the film thickness is not uniform in an area with large scale, we cannot image the vortices because the tip can easily bump into a terrace.

We observe twofold symmetric QPI patterns on the 2QL Bi$_2$Te$_3$/FeTe$_{0.55}$Se$_{0.45}$ heterostructures at small energies both in positive and negative bias within the superconducting gap maximum, which naturally suggests a twofold symmetry of the superconducting gap for the proximity-induced superconductivity on the Bi$_2$Te$_3$ films. One may argue that the twofold nature is related to the supermodulations on the BiO surface [55] of the Bi2212 substrate. We argue that this is unlikely because we do not see any features related to the striped supermodulations on either the topography or the QPI mappings measured on the Bi$_2$Te$_3$ films. Furthermore, the FT-QPI patterns beyond the gap maximum show sixfold symmetric spots without any intensity variation of twofold symmetry, and this contrasts the fact that if the supermodulation would have given influence on the electronic properties of the Bi$_2$Te$_3$ films. In addition, with control experiments, we convince that the twofold symmetric FT-QPI patterns or the twofold symmetric superconducting gap are the nature properties of the Bi$_2$Te$_3$ film on Bi2212. Although the characteristic scattering spots in terms of scattering vectors are distinct at energies beyond the maximum gap (corresponding to the normal state) between the 2QL Bi$_2$Te$_3$/FeTe$_{0.55}$Se$_{0.45}$ and the 2QL Bi$_2$Te$_3$/Bi2212 heterostructures as discussed above, the gap minimum directions for these two kinds of proximity-induced superconducting gaps are however both along one pair of ΓM directions or one of the principal crystalline axes of the top layer of the Bi$_2$Te$_3$ film. Theoretically, it was proposed that two kinds of pairing symmetries for the odd-parity topological superconducting gaps [39] may exist in the system, namely the Δ$_{4x}$ and Δ$_{1y}$ notations. For the Δ$_{1y}$ notation, the gap minima should be along one pair of the principal crystalline axes, while for the Δ$_{4x}$ notation, the gap minima, perhaps in form of nodes, is along the perpendicular direction. Although we cannot judge whether the gap has nodes on the 2QL Bi$_2$Te$_3$/Bi2212 heterostructures, the gap min-
imum direction determined here allows us to conclude that the nodeless $\Delta_{\uparrow\downarrow}$ notation proposed theoretically is a more possible gap structure in the present system. Our work provides extra evidence for the existence of topological superconductivity induced by proximity effect on the Bi$_2$Te$_3$/Bi2212 heterostructures.

V. CONCLUSION

To conclude, by growing Bi$_2$Te$_3$ films on cleaved surface of high-$T_c$ cuprate Bi2212, we successfully achieve proximity-induced superconductivity in the topological insulator layer. The superconducting gap maximum on the 2QL Bi$_2$Te$_3$/Bi2212 heterostructures is as large as 7.6 meV which is determined from the tunneling spectrum measurements and Dynes model fittings, and the gap feature remains even when the topological insulator film is as thick as 5 QLs. The intensity of FT-QPI patterns show the twofold symmetric nature when measured at energies within the superconducting gap maximum, which suggests a twofold symmetry of the superconducting gap on the Bi$_2$Te$_3$ film. The orientation of the gap minimum is along one of the principal crystalline axes, which is consistent with the theoretically proposed $\Delta_{\uparrow\downarrow}$ notation. This gap structure is the same as the one discovered in our previous measurements on the 2QL Bi$_2$Te$_3$/FeTe$_{0.55}$Se$_{0.45}$ heterostructures. Our observations provide clear evidence of proximity-induced superconductivity possibly with topological nature on this kind of heterostructures consisted by the TI and high-$T_c$ cuprates.

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