Full superconducting gap in the doped topological crystalline insulator, Sn$_{0.6}$In$_{0.4}$Te

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The thermal conductivity of the doped topological crystalline insulator, Sn$_{0.6}$In$_{0.4}$Te superconducting single crystal with $T_c = 4.1$ K, was measured down to 50 mK. It is found that the residual linear term $\kappa_0/T$ is negligible in zero magnetic field. The $\kappa_0/T$ shows a slow field dependence at low magnetic field. These results suggest that the superconducting gap is nodeless, unless there exist point nodes with directions perpendicular to the heat current. Due to its high-symmetry fcc crystal structure of Sn$_{0.6}$In$_{0.4}$Te, however, such point nodes can be excluded. Therefore we demonstrate that this topological superconductor candidate has a full superconducting gap in the bulk. It is likely the unconventional odd-parity $A_{1u}$ state which supports a surface Andreev bound state.

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I. INTRODUCTION

Three dimensional (3D) topological insulators (TIs) have attracted great attentions in recent years because of their novel quantum states. They are characterized by an inverted gap in the bulk caused by strong spin-orbit coupling (SOC) and a gapless surface state protected by time-reversal symmetry. In the layered compound Bi$_2$Se$_3$, a typical 3D TI, superconductivity was found by intercalating Cu atoms between the Se layers. Cu$_x$Bi$_2$Se$_3$ is considered as a promising candidate of topological superconductor with potential applications in topological quantum computing. Recently, Fu proposed a new type of materials named topological crystalline insulator (TCI), in which the gapless surface state is protected by mirror symmetry of the crystal, instead of time-reversal symmetry. Later, SnTe with face-centered-cubic (fcc) crystal structure was predicted to be such a TCI, and this prediction was soon confirmed by angle-resolved photoemission spectroscopy (ARPES) measurements.

Superconductivity exists in Sn$_{1-x}$In$_x$Te, with Sn partially substituted by In. The superconducting transition temperature $T_c$ is about 1.2 K at low doping $x = 0.045$. With increasing the doping level, $T_c$ increases to a maximum, about 4.6 K at $x = 0.45$. Zero-bias conductance peak (ZBCP) was observed in Sn$_{1-x}$In$_x$Te ($x = 0.045$) by using point-contact spectroscopy technique which suggests the existence of Andreev bound state (ABS). The ARPES measurements also support the presence of topological surface state in Sn$_{1-x}$In$_x$Te ($x = 0.045$) by comparing to pristine SnTe. These results indicate that Sn$_{1-x}$In$_x$Te is another candidate of topological superconductor.

Although the surface state of Sn$_{1-x}$In$_x$Te has been clarified, the superconducting gap in its bulk is still unknown. Theoretically, an unconventional odd-parity $A_{1u}$ state with full superconducting gap in the bulk is usually required for topological superconductors. However, the odd-parity pairing state with point nodes in the gap ($A_{2u}$ state) is also allowed. In this context, it is very important to determine the superconducting gap structure of Sn$_{1-x}$In$_x$Te in the bulk.

Ultra-low-temperature thermal conductivity measurement is a bulk technique to probe the gap structure of superconductors. A negligible residual linear term $\kappa_0/T$ in zero magnetic field is a strong evidence for nodeless superconducting gap. Line nodes will result in a finite and universal (impurity independent) $\kappa_0/T$. Point nodes will cause a nonuniversal finite $\kappa_0/T$ if the impurity scattering rate is high, unless the direction of point nodes is perpendicular to the heat current. Furthermore, the field dependence of $\kappa_0/T$ can give more information on nodal gap, the gap anisotropy, or multiple gaps.

In this paper, we present the ultra-low-temperature thermal conductivity measurements of Sn$_{0.6}$In$_{0.4}$Te single crystal with $T_c = 4.1$ K, which has a relatively low residual resistivity thus suits for heat transport study. We find a negligible $\kappa_0/T$ in zero field and a slow field dependence of $\kappa_0/T$ at low field. By considering its high-symmetry fcc crystal structure, we exclude superconducting gap with point nodes ($A_{2u}$ state), and conclude that Sn$_{0.6}$In$_{0.4}$Te has a full superconducting gap in the bulk ($A_{1u}$ state).

II. EXPERIMENT

The Sn$_{0.6}$In$_{0.4}$Te single crystals were grown by modified Bridgman method. The dc magnetic susceptibility was measured by using a superconducting quantum interference device (MPMS, Quantum Design). The (100) plane was identified by X-ray diffraction measurements. The sample for transport measurements was cut and polished to a rectangular shape of $2.6 \times 1.6$ mm$^2$ in the (100) plane, with the thickness of 0.31 mm. Four silver wires were attached to the sample with silver paint, which were used for both resistivity and thermal conductivity measurements, with the high-symmetry fcc crystal structure of Sn$_{0.6}$In$_{0.4}$Te, the contacts are metallic with typical resistance 20 m$\Omega$ at 2 K. The thermal conductivity was measured in a dilution refrigerator, using a standard four-wire steady-
FIG. 1: (Color online). (a) Low-temperature magnetization of Sn$_{0.6}$In$_{0.4}$Te single crystal measured with zero-field-cooled (ZFC) process. (b) Temperature dependence of resistivity of Sn$_{0.6}$In$_{0.4}$Te single crystal at zero field. Insert shows the resistive superconducting transition at low temperature.

**III. RESULTS AND DISCUSSION**

Figure 1(a) shows the low-temperature magnetization of Sn$_{0.6}$In$_{0.4}$Te single crystal. The onset of superconducting transition is at 4.0 K. The magnetization saturates below 2.6 K and the shielding fraction at 2 K is estimated to be $\sim 93\%$, showing the bulk superconductivity in our sample. The temperature dependence of resistivity at zero field is shown in Fig. 1(b). From the inset of Fig. 1(b), the width of the resistive superconductivity transition (10-90%) is 0.27 K, and the $T_c$ defined by $\rho = 0$ is 4.1 K. The $\rho(T)$ curve from $T_c$ to 10 K is quite flat, which extrapolates to a residual resistivity $\rho_0 = 0.233$ m$\Omega$ cm. Thus the residual resistivity ratio $\rho(300 \, K)/\rho_0 \approx 1.5$ is obtained. This value is slightly larger than that in Ref. 14, indicating higher quality of our sample.

Figure 2(a) shows the low-temperature resistivity of Sn$_{0.6}$In$_{0.4}$Te single crystal in magnetic fields up to 1.8 T. To estimate the upper critical field $H_{c2}(0)$, the temperature dependence of $H_{c2}(T)$, defined by $\rho = 0$, is plotted in Fig. 2(b). $H_{c2}(0) \approx 1.7$ T is roughly estimated. A slightly different $H_{c2}(0)$ does not affect our discussion on the field dependence of $\kappa_0/T$ below.

The temperature dependence of thermal conductivity for Sn$_{0.6}$In$_{0.4}$Te single crystal in zero and magnetic fields are plotted as $\kappa/T$ vs $T$ in Fig. 3. The measured thermal conductivity contains two contributions, $\kappa = \kappa_e + \kappa_p$, which come from electrons and phonons, respectively. In order to separate the two contributions, all the curves...
below 0.3 K were fitted to $\kappa / T = a + bT^{-\alpha - 1}$. The two terms $aT$ and $bT^\alpha$ represent contributions from electrons and phonons, respectively. The residual linear term $\kappa_0 / T \equiv a$ is obtained by extrapolated $\kappa / T$ to $T = 0$ K. Because of the specular reflections of phonons at the sample surfaces, the power $\alpha$ in the second term is typically between 2 and 3.

We first check the high-field normal-state thermal conductivity. In $H_{c2}(0) = 1.7$ T, the fitting gives $\kappa_0 / T = 0.100 \pm 0.004$ mW K$^{-2}$ cm$^{-1}$ and $\alpha = 2.45 \pm 0.05$. This value of $\kappa_0 / T$ roughly agrees with the normal-state Wiedemann-Franz law expectation $L_0 / \rho_0 = 0.105$ mW K$^{-2}$ cm$^{-1}$, with the Lorenz number $L_0 = 2.45 \times 10^{-8}$ W Ω K$^{-2}$ and $\rho_0 = 0.233$ mΩ cm. The verification of the Wiedemann-Franz law in the normal state demonstrates that our thermal conductivity measurements are reliable. For the power $\alpha$, previously $\alpha \approx 2.2$ was found in the s-wave superconductor Cu$_2$TiSe$_2$ and recently, $\alpha \approx 2$ has been observed in some iron-based superconductors such as BaFe$_{1.9}$Ni$_{0.1}$As$_2$, KFe$_2$As$_2$ and Ba(Fe$_{1-x}$Ru$_x$)$_2$As$_2$. Below we will only concentrate on electron contribution.

In zero field, $\kappa_0 / T = 0.003 \pm 0.002$ mW K$^{-2}$ cm$^{-1}$ is obtained by the fitting. Note that this value is within our experimental error bar $\pm 0.005$ mW K$^{-2}$ cm$^{-1}$. Therefore the $\kappa_0 / T$ of Sn$_0.6$In$_{0.4}$Te in zero field is negligible, comparing to the normal-state $\kappa_0 / T = 0.100$ mW K$^{-2}$ cm$^{-1}$ in $H_{c2}(0) = 1.7$ T. For s-wave nodeless superconductors, there are no fermionic quasiparticles to conduct heat when $T \to 0$ since all electrons become Cooper pairs. Therefore, there is no residual linear term of $\kappa_0 / T$, as seen in Nb and InBi. In contrast, a finite $\kappa_0 / T$ in zero field is usually observed in a superconductor with nodal gap, if the heat current is not perpendicular to the nodal directions. For example, $\kappa_0 / T = 1.41$ mW K$^{-2}$ cm$^{-1}$ was observed with heat current in the $ab$ plane for the overdoped cuprate Tl$_2$Ba$_2$CuO$_{4+x}$ (Tl-2201), a d-wave superconductor with $T_c = 15$ K. However, if the heat current is perpendicular to the nodal directions, the $\kappa_0 / T$ will be zero despite the existence of gap nodes. The negligible $\kappa_0 / T$ of our Sn$_0.6$In$_{0.4}$Te single crystal in zero field suggests a nodeless superconducting gap, but the existence of nodes with directions perpendicular to the heat current is still possible.

Since both unconventional odd-parity states $A_{1u}$ (full superconducting gap) and $A_{2u}$ (gap with point nodes) are allowed in Sn$_{1-x}$In$_x$Te from previous surface experiments, here we show how the $A_{2u}$ state can be excluded from our bulk measurements by further considering its impurity scattering rate and symmetry of crystal structure. For a superconductor with point nodes in the gap, the observation of a finite $\kappa_0 / T$ requires a relatively high impurity scattering rate. We estimate the normal state scattering rate $\Gamma_0$ of our Sn$_0.6$In$_{0.4}$Te from $\rho_0$ and the plasma frequency $\omega_p = c / \lambda_0$, in which $c$ is the speed of light and $\lambda_0$ is the penetration depth when $T \to 0$ ($\lambda_0 = 860$ nm according to ref. 14). With the formula $\Gamma_0 \approx \frac{2}{3} \frac{\rho_0}{\lambda_0^{1.5}}$...
\[ \Gamma_0 = \left( \frac{\omega_N^2}{8\pi} \rho_0 \right), \quad H_0/k_B T_c = 2.9 \] is obtained. This value is high enough to lead to a finite \( \kappa_0/T \). Since we do not observe \( \kappa_0/T \) in \( \text{Sn}_x\text{In}_{1-x} \text{Te} \), the directions of the point nodes, if they do exist, must be perpendicular to the heat current. However, due to the high-symmetry fcc crystal structure of \( \text{Sn}_x\text{In}_{1-x} \text{Te} \), such a configuration is impossible. In other words, one can not let all the directions of point nodes be perpendicular to the heat current at the same time. For example, in our heat transport experiments, if there is point nodes along the [100] direction which is perpendicular to our heat current, there must also be point nodes along the [010] and [001] directions, which can not be perpendicular to our heat current simultaneously. From above analysis, we can safely exclude the \( A_2 \) state with point nodes in \( \text{Sn}_x\text{In}_{1-x} \text{Te} \), and its superconducting state should be the fully gapped \( A_{1u} \) state.

The field dependence of \( \kappa_0/T \) will give more information of the superconducting gap structure. Between \( H = 0 \) and 1.7 T, we fit all the curves and obtain the \( \kappa_0/T \) for each magnetic field. The normalized \( \kappa_0(H)/T \) as a function of \( H/H_0 \) for \( \text{Sn}_0.6\text{In}_{0.4} \text{Te} \) is plotted in Fig. 4. For comparison, similar data of the clean s-wave superconductor \( \text{Nb} \), the dirty s-wave superconducting alloy \( \text{InBi} \) and an overdoped d-wave cuprate superconductor \( \text{Ti}_2\text{2201} \) are also plotted. The slow field dependence of \( \kappa_0/T \) at low field for Nb and InBi manifests their full superconducting gap. From Fig. 4, the curve of the normalized \( \kappa_0(H)/T \) for \( \text{Sn}_0.6\text{In}_{0.4} \text{Te} \) is close to that of the dirty s-wave superconductor \( \text{InBi} \), which further supports a full superconducting gap.

To check whether \( \text{Sn}_0.6\text{In}_{0.4} \text{Te} \) is a dirty superconductor, we estimate its superconducting coherence length \( \xi_0 \) and the electron mean free path \( l \). From \( H_0(0) = 1.7 \) T, we obtain \( \xi_0 \approx 142 \text{ Å} \) through the relation \( H_0(0) = \Phi_0/2\pi\xi_0^2 \). The electron mean free path is estimated using the normal-state thermal conductivity \( \kappa_N \), specific heat \( c \), and the Fermi velocity \( v_F \). Since \( \kappa_N = (1/3)cv_Fl \), we have the relation \( l = \beta(\kappa_N/T)/(\gamma v_F) \) where \( \gamma = c/T \) is the linear specific heat coefficient and \( v_F \) can be calculated through \( \xi_0 \equiv h v_F/\gamma \Delta(0) \) and \( \Delta(0) = 1.76k_B T_0/2 \)

With \( \xi_0 \approx 0.100 \text{ mW K}^{-2} \text{ cm}^{-1} \), \( \gamma = 2.62 \text{ mJ mol}^{-1} \text{ K}^{-2} \), and the calculated \( v_F = 0.28 \text{ eV Å} \), we get \( l \approx 11 \text{ Å} \). Since \( l \ll \xi_0 \), \( \text{Sn}_0.6\text{In}_{0.4} \text{Te} \) is indeed a dirty superconductor.

IV. SUMMARY

In summary, we have measured the thermal conductivity of \( \text{Sn}_0.6\text{In}_{0.4} \text{Te} \) single crystal down to 50 mK. The negligible \( \kappa_0/T \) at zero field and the slow field dependence of \( \kappa_0/T \) at low field suggest nodeless superconducting gap, and the possibility of point nodes perpendicular to the heat current is excluded due to the high-symmetry fcc crystal structure. Combining with previous surface experiments, our new bulk measurements demonstrate that the superconducting state in \( \text{Sn}_1\text{In}_2 \text{Te} \) is likely an unconventional odd-parity \( A_{1u} \) state with fully superconducting gap, if it is indeed a topological superconductor.

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