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SPECIAL TOPIC — Unconventional superconductivity

Tip-induced superconductivity commonly existing in the family of transition-metal dipnictides MPn_2*

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We report the tip-induced superconductivity on the topological semimetal $NbSb_2$, similar to the observation on $TaAs_2$ and $NbAs_2$. Belonging to the same family of MPn_2, all these materials possess similar band structures, indicating that the tip-induced superconductivity may be closely related to their topological nature and share a common mechanism. Further analysis suggests that a bulk band should play the dominant role in such local superconductivity most likely through interface coupling. In addition, the compatibility between the induced superconductivity and tips' ferromagnetism gives an evidence for its unconventional nature. These results provide further clues to elucidate the mechanism of the tip-induced superconductivity observed in topological materials.

Keywords: tip-induced superconductivity, topological, mechanism

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1. Introduction

Topological materials, possessing a novel state with nonzero topological invariant and exotic surface states, have attracted considerable attention in condensed matter physics and material science in the last decade.[1–3] Whereupon, the concept of topological superconductivity with a gapped superconducting bulk state and gapless surface states was proposed by combining topological natures with superconductivity. Topological superconductivity is potentially useful for fault-tolerant quantum computing to significantly improve its efficiency. Intensive theoretical and experimental researches have been carried out in searching for topological superconductors (TSCs), e.g., charge carrier doping, high pressure, and proximity effect.[4–18] Very recently, tip-induced superconductivity (TISC) was observed in a variety of non-superconducting topological semimetals by means of point-contact (PC),[19–27] which had aroused great enthusiasm in the research of topological superconductivity. So far, superconductivity has been induced in various topological materials, however, whether these phenomena share a common mechanism is still in debate.

In an earlier work,[27] we have successfully achieved tip-induced superconductivity on the topological semimetals $TaAs_2$ and $NbAs_2$, which are the members of the transition-metal dipnictides MPn_2 (M = Ta, Nb; Pn = P, As, Sb). A universal relationship between the zero-temperature upper critical field $H_{c2}(0)$ and the critical temperature T_c was uncovered for both compounds and different crystal orientations. The findings identify a bulk band rather than surface states playing the dominant role in the induced superconductivity. The consistent results predict a great possibility to realize superconduc-

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tivity in other members of the MPn_2 family possessing similar band structures.

In this paper, we performed PC experiments on $NbSb_2$, another member of the MPn_2 family[28,29] and successfully achieved TISC, yielding the same universal $H_{c2}(0)$ vs. T_c relationship for $TaAs_2$ and $NbAs_2$. This suggests that the TISC on topological materials may have a common mechanism related to their specific band features. It was also found that local superconductivity can be triggered by magnetic tips of Co and Ni as well as nonmagnetic tips, implying an unconventional pairing component.

2. Experiment

High-quality $NbSb_2$ single crystals here were synthesized via a chemical vapor transport method using I_2 as the carrier agent. Figure 1(a) presents the room temperature x-ray diffraction (XRD) showing four peaks which can be indexed as $(20\bar{1})$ reflections in space group $C12/m1$ (No. 12). The chemical ratio determined by energy dispersive x-ray spectroscopy (EDS) is consistent with 1 : 2 for Nb : Sb. Figure 1(b) shows the temperature dependence of resistance obtained with the standard four-probe method at zero field, demonstrating a metallic like behavior. No resistance drop could be detected down to 1.9 K, excluding the presence of a superconducting impurity phase. As displayed in Fig. 1(c), the raw data of magnetization versus temperature under 20 Oe are temperature independent without diamagnetic transition down to 2 K, also indicating that no superconducting phase exists in the bulk, which is similar to the cases of $TaAs_2$ and $NbAs_2$.[27,30,31]

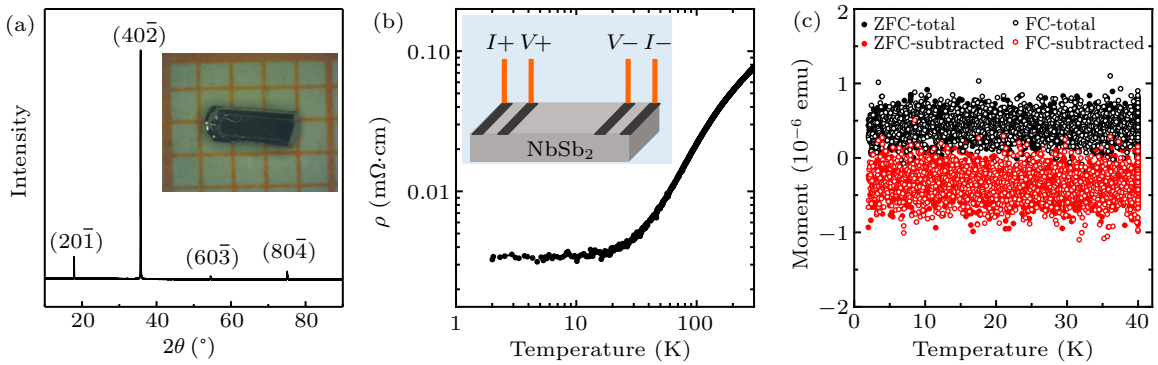


Fig. 1. Sample information of the studied $NbSb_2$ single crystals. (a) X-ray diffraction pattern, only showing the peaks indexed as $(20\bar{1})$ reflections. Inset: Photograph of a single crystal. (b) Temperature-dependent resistance obtained with the four-probe method at zero field. Inset: Configuration of the standard four-probe method measurement. (c) Magnetization vs. temperature taken in zero-field-cooling (ZFC) and field-cooling (FC) processes, respectively. The total signal and background signal for empty holders have been measured. The ZFC-subtracted and FC-subtracted signals were obtained by subtracting the background signals from the total signals. The applied magnetic field was 20 Oe.

PC experiments were performed with a "needle-anvil" configuration [as sketched in the left inset of Fig. 2(a)] using our homebuilt probes based on a physical property measurement system (PPMS). An ultrafine differential micrometer was used to drive a tip towards to the $(20\bar{1})$ plane of $NbSb_2$. The tips were made of gold (Au), nickel (Ni), or cobalt (Co). During the measurements, the current–voltage characteristics (I–V) and differential conductance spectra ($\mathrm{d}I/\mathrm{d}V$–V) were recorded simultaneously using a quasi-four-probe scheme and a standard lock-in method.

3. Results and discussion

Figure 2(a) shows a series of spectra taken at a PC formed between a $NbSb_2$ single crystal and an Au tip. The low temperature spectra exhibit a spurious zero-bias conductance peak (ZBCP) accompanied by two symmetric conductance dips. These features are most probably caused by the critical current effect, the same as that on previously studied $TaAs_2$ or $NbAs_2$.[27] Under this circumstance, i.e., the thermal regime, inelastic scattering of electrons causes Joule heating and a local rise in temperature. Hence, a superconducting-to-normal transition will occur at a critical current I_c,[32,33] resulting in the ZBCP and dips mentioned above. The ZBCP resulted from the critical current effect is extrinsic, from which we could not determine the amplitude of the superconducting gap or pairing symmetry, though an unconventional superconductor, e.g., with a p- or d-wave pairing, can give an intrinsic ZBCP for some specific current injecting directions due to the formation of Andreev bound states.[7,32,34–37] Nonetheless, superconducting transition temperature T_c and upper critical field H_{c2} can be determined from the temperature and field evolutions of the measured PC spectra, since the spectral features originate from superconductivity and vanish at the critical temperatures or fields. Thus, we define T_c (H_{c2}) as the temperature (magnetic field) where the superconducting signal is completely suppressed. Figure 2(b) shows the field dependent spectra of the same PC in Fig. 2(a) where the spectra features decay gradually with the increasing field. Figure 2(c) shows the temperature-dependent zero-bias resistance (ZBR) curves extracted from the temperature evolutions of the PC spectra obtained under various magnetic fields. The super-

conducting transition shifted continuously to lower temperature with increasing field from which we could determine $H_{c2}(T)$ by the points where the superconducting features vanish. The obtained parameters fulfill the empirical formula of $H_{c2}(T) = H_{c2}(0)[1-(T/T_c)^2]$ with $T_c \sim 5.75$ K and $H_{c2}(0) \sim 2.1$ T, as demonstrated in Fig. 2(d).

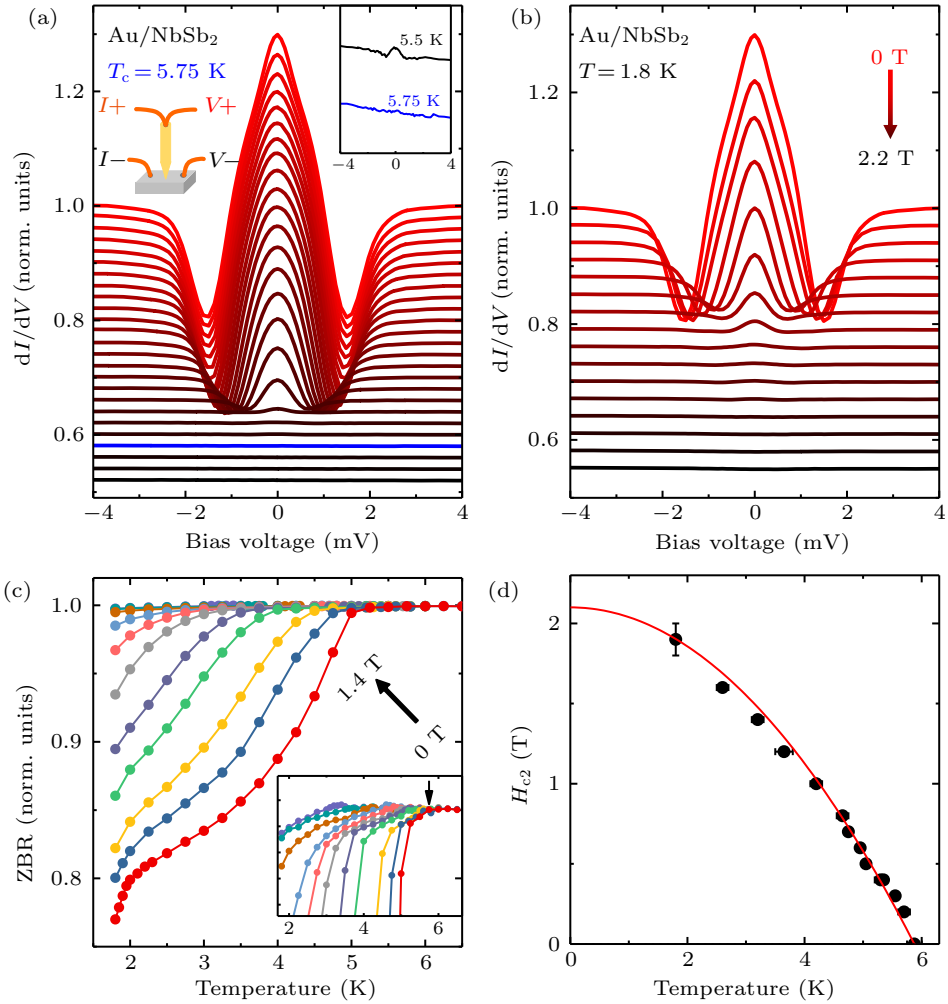


Fig. 2. Evidences of TISC at Au/$NbSb_2$ point contacts. (a) Temperature evolutions of PC spectra from 1.8 K to 6.5 K, the temperature intervals are 0.05 K between 1.8 K and 2.0 K, 0.1 K between 2.0 K and 2.3 K, and 0.25 K above 2.3 K. The curve around the critical temperature is denoted by the blue line. The spectra have been normalized and shifted for clarity (similarly hereinafter). Left inset: Schematic diagram of the PC measurement configuration. Right inset: Zoom in the spectra near T_c. (b) Magnetic field evolutions of the PC spectra taken at the same PC in (a). The field is applied perpendicular to the plane of the sample (similarly hereinafter), with a step of 0.2 T between 0 T and 0.2 T, a step of 0.1 T between 0.2 T and 0.8 T, a step of 0.2 T between 0.8 T and 1.8 T, and a step of 0.1 T between 1.8 T and 2.0 T. (c) Temperature-dependent ZBR taken from the spectra measured under various magnetic fields. Inset: Details near the superconducting transitions. (d) $H_{c2}(T)$ determined from the temperature evolutions of the PC spectra measured under various magnetic field. The solid line indicates an empirical formula of $H_{c2}(T) = H_{c2}(0)[1-(T/T_c)^2]$ with appropriate parameters.

In order to get further insight into the induced superconductivity detected at the PCs on $NbSb_2$, we have studied a series of PCs formed with various metal tips (including nonmagnetic tips of Au and ferromagnetic tips of Ni and Co). As exemplified in Figs. 3(a) and 3(b), similar to $TaAs_2$ and $NbAs_2$, local superconductivity can also be triggered on $NbSb_2$ by ferromagnetic tips of Ni and Co as well as the nonmagnetic tip of Au. The experimental occasionality can be ruled out due to the great repeatability of the experiments. It is well known that ferromagnetism will suppress conventional superconductivity by breaking spin-singlet paring.[38–40] Hence the compatibility between TISC and ferromagnetism indicates its unconventional nature.[41–44]

The statistics of the determined T_c and $H_{c2}(T)$ are displayed in Fig. 4 to be compared with the results of $TaAs_2$ and $NbAs_2$. Figure 4(a) summarizes the T_c distributions for various tips varying from 2.2 K to 6.1 K. Apparently, the TISC on $NbSb_2$ is independent of tip materials, and the wide distributions of T_c are most likely a consequence of the variable coupling strength for different practical micro-constrictions, which is consistent with the results obtained on $TaAs_2$ and $NbAs_2$. Figure 4(b) shows the $H_{c2}(T)$ relationships for the $(20\bar{1})$ plane of $NbSb_2$. By fitting all $H_{c2}(T)$s to the empirical formula, the phase diagram of $H_{c2}(0)$ vs. T_c is determined and shown in Fig. 4(c), which is coincident with the results of $TaAs_2$ and $NbAs_2$. The points with relatively higher

upper critical fields fall into the universal trend of $H_{c2}(0) \propto T_c^{1.5}$ (thicker solid line).[27] It is worth noting that the TISC has been realized on various topological materials,[19–27,45] whereas it has been rarely reported on the conventional metals, suggesting that the TISC on topological materials maybe closely related to their topological properties and share the same origin. That is to say, such TISC on MPn_2 family most likely originates from the interface coupling between the tips and samples. Furthermore, variable T_c value indicates the importance of the interface coupling strength between the tips and samples. In particular, the consistency of $H_{c2}(0)$ vs. T_c among different members of the MPn_2 family, in spite of their distinct surface states, suggests that the induced local superconductivity mainly originates from their bulk band with similar features.[27] However, there are several points having lower upper critical fields, of which we could not trace their origin for the time being. As a rational conjecture, it may be affected accidentally by the surface states or some other bands considering the multiband nature of the MPn_2 family.

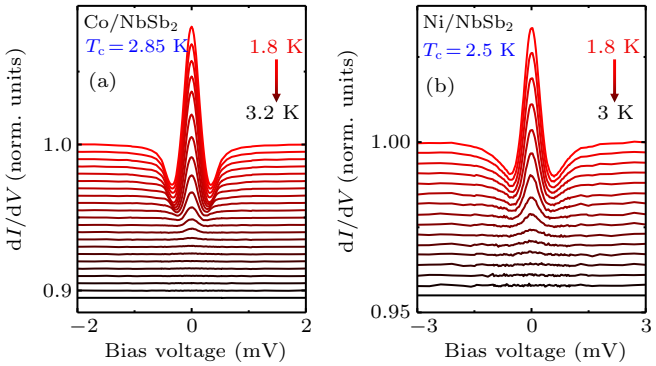


Fig. 3. Evidences of TISC using ferromagnetic tips on $NbSb_2$. (a) A set of PC spectra measured at a Co/$NbSb_2$ point contact from 1.8 K to 3.2 K. (b) A set of PC spectra measured at a Ni/$NbSb_2$ point contact from 1.8 K to 3.0 K.

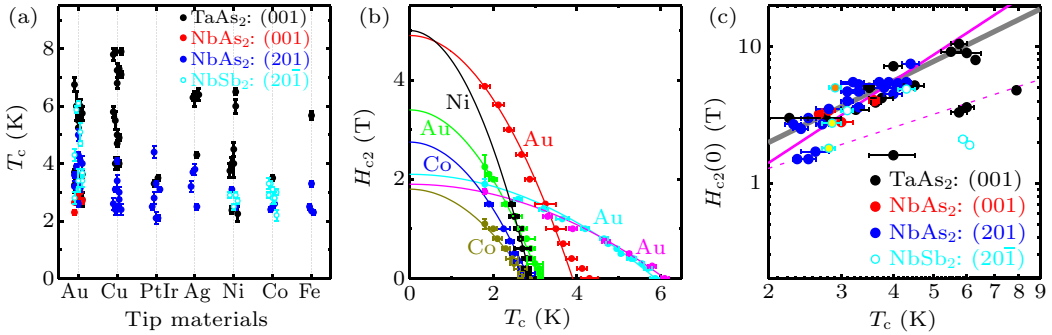


Fig. 4. Statistics of T_c and H_{c2} of MPn_2.[27] (a) T_c values achieved on the (20$\bar{1}$) plane of $NbSb_2$ compared with the results of $TaAs_2$ and $NbAs_2$. (b) $H_{c2}(T)$ obtained on $NbSb_2$ using various metal tips. The solid lines are plotted according to an empirical formula with appropriate parameters. (c) Relationship of $H_{c2}(0)$ vs. T_c plotted on a double logarithmic scale obtained from several PCs on $NbSb_2$ compared with the results of $TaAs_2$ and $NbAs_2$, where the tip materials of the cyan open circles filled with white, yellow, and orange are Au, Co, and Ni, respectively.

4. Conclusion

In summary, we have induced local superconductivity at point contacts formed on the $NbSb_2$ single crystals using both nonmagnetic tips and ferromagnetic tips, which can be divided into two categories according to the values of the upper critical field. This is in good agreement with the results of $TaAs_2$ and $NbAs_2$ studied previously. The findings here confirm the previous expectation and indicate that the topological nature may play an important role in TISC. The consistent results from different members of the MPn_2 family support that bulk bands, instead of surface states, are the major origin of the induced superconductivity. Therefore, MPn_2 is a good platform for further understanding the mechanism of TISC.

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