Enhancement of the superconductivity and quantum metallic state in the thin film of superconducting Kagome metal KV_3Sb_5

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Recently V-based Kagome metal attracted intense attention due to the emergence of superconductivity in the low temperature. Here we report the fabrication and physical investigations of the high quality single-crystalline thin films of the Kagome metal KV_3Sb_5. For the sample with the thickness of about 15 nm, the temperature dependent resistance reveals a Berezinskii-Kosterlitz-Thouless (BKT) type behavior, indicating the presence of two-dimensional superconductivity. Compared with the bulk sample, the onset transition temperature T_c^{onset} and the out-of-plane upper critical field H_{c2} are enhanced by 15% and more than 10 times respectively. Moreover, the zero-resistance state is destroyed by a magnetic field as low as 50 Oe. Meanwhile, the temperature-independent resistance is observed in a wide field region, which is the hallmark of quantum metallic state. Our results provide evidences for the existence of unconventional superconductivity in this material.

Materials with Kagome lattice manifest abundant exotic quantum phenomena including geometric spin frustration, non-trivial topological states, charge and spin density wave orders, etc [1–3]. The discovery of superconductivity in the Kagome metal AV_3Sb_5 (A = K, Rb, Cs) added a new physical dimension to this novel system [4–7]. Theoretically the unconventional pairing has been proposed for this material due to the proximity to the multiple van Hove singularities of the superconducting (SC) state [8]. In the experimental side, the double-dome-shaped evolution of the SC transition temperature T_c with pressure has been confirmed by several groups. [9–11] Concerning the gap structure, the conclusions from different techniques are still inconsistent [12, 13]. The observation of zero-bias conductance peak inside the vortex core indicates the possibility for the Majorana bound states [14]. These experimental results initially show the signs of unconventional superconductivity. Currently more solid experimental results are necessary in order to confirm the unconventional behaviors of this material. It is an important perspective to investigate the physical performances in low dimension. Actually, in recent years, two-dimensional (2D) superconductivity has drawn great interest due to the emergence of new quantum phenomena, including Ising superconductivity [15–18], quantum metallic state [19–23], Berezinskii-Kosterlitz-Thouless (BKT) transition [24–26], and even the significant enhancement of T_c [27–30]. Thus, revealing the performance of SC properties in the low dimension is vary crucial in understanding the intrinsic properties of this material.

In this Letter, we report the mechanical exfoliation and superconducting properties of the thin film of KV_3Sb_5. Both the onset transition temperature T_c^{onset} and the out-of-plane upper critical field H_{c2} are enhanced significantly in the thin samples. Two-dimensional superconductivity is revealed by both the BKT-type resistance transition and the logarithmic evolution of the flux-flow activation energy. Strikingly, a transition from the superconducting to quantum metallic state is induced by a very small perpendicular magnetic field (∼50 Oe), while the onset transition point is only moved to about 0.5 K by the magnetic field as high as 6000 Oe. The present work reveals the unconventional behaviors in Kagome superconductors and also provides an important platform to study the dimensionality effect of this system.

The KV_3Sb_5 single crystals were grown by the self-flux method [4]. Utilizing the characteristics of layered structure, the mechanical exfoliation method was adopted. The KV_3Sb_5 thin flake is exfoliated from its single crystal by scotch tape and transferred onto SiO_2/Si substrate (SiO_2-300 nm; Si-500 μm) [31]. Typically the in-plane dimension of the fabricated samples can be as large as 200 μm. All the studies in this work are carried out on samples with a thickness of 15 nm. The electrical transport data were collected on the dilution refrigerator based on the physical property measurement system (Quantum Design, PPMS) by a standard four-probe method, and the silver paste was used to prefabricate the electrodes. The external magnetic field was applied perpendicular to sample surface and the electric current. The applied electric current is 10 μA.

Temperature dependence of resistance of the thin KV_3Sb_5 sample is shown in Fig. 1. The thickness of this sample is estimated to be 15 nm from the comparison of the resistance of the thin and bulk samples. A SC transi-

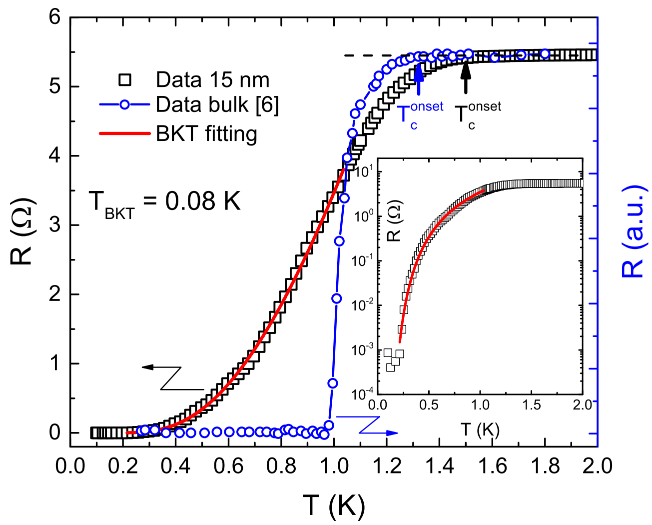

FIG. 1: (color online) Temperature dependence of resistance of KV_3Sb_5 thin film at zero magnetic field. The data of the bulk sample [6] is also shown for comparison (right axis). The red line is the fitting curve representing the BKT transition (see text). Shown in the lower right inset is the same data using a semilog scale.

tion is observed in the low temperature. The onset transition temperature is enhanced by about 0.2 K as compared with that of the bulk sample [6]. Considering the rather low transition temperature in this material, actually this enhancement reaches the extent as high as 15%. In sharp contrast, the zero-resistance temperature (∼0.22 K) is much lower as compared with the bulk sample, revealing a tail-like feature in a wide temperature range. Similar behaviors have been reported in other 2D SC materials, which were explained in terms of the Berezinskii-KosterlitzThouless (BKT) transition [22, 26, 32]. Based on this picture, the zero-resistance state is driven by the binding of vortex-antivortex pairs. As shown by the red cure in Fig. 1, the experimental data can be well described by the equation [32, 33],

$$R = R_0 \exp[-b(\frac{T}{T_{BKT}} - 1)]^{-1/2}, \quad (1)$$

which demonstrates the occurrence of BKT transition. The BKT transition temperature is determined to be $T_{BKT} = 0.08$ K. The BKT-type behavior suggests preliminarily that 2D superconductivity is achieved at zero magnetic field in our sample. Considering the fact that the upper critical field is only several hundred osters in the bulk sample [6], the coherence length should be relatively large. Thus, it's rather reasonable that a film with the thickness of 15 nm can meet the requirement of two-dimensional limit.

We next focus on the electrical transport behaviors under out-of-plane magnetic field. As shown in Fig. 2(a), the $R-T$ curves show the systematically evolution with the increase of field. These data provide three important messages that need to be emphasized in particular. Firstly, as shown in Fig. 2(b), the magnetic field as high as 6000 Oe suppresses the onset transition temperature T_c^{onset} (determined using the criterion 99% R_n) from 1.5 K to 0.5 K, which indicates a rather high upper critical field above 6000 Oe. This value is more than 10 times higher than that of the bulk samples [6]. Secondly, the zero-resistance state is destroyed by the magnetic field as low as 50 Oe, suggesting a very narrow flux solid state (if it exists). Thirdly, the temperature-independent resistance is observed in a very wide field range from 50 to 6000 Oe, which is a hallmark of the quantum metallic state [19, 22]. These striking features unambiguously demonstrate the dimensional effect of this system.

In order to further understand the unconventional temperature-independent behavior of the $R-T$ curves, we plot the Arrhenius plots (ln$R$ vs $1/T$) under several typical fields in Fig. 3(a). LnR shows a transformation from the linear evolution to the $1/T$-independent tendency with the increase of $1/T$, which are represented by the dashed and dotted lines respectively. The intersections of the dashed and dotted lines are used to determine the transition temperature between the two behaviors. The linear relation is the consequence of the thermal activated flux flow (TAFF) behavior, where the resistance R obeys the relationship [34, 35]

$$R = R_0 \exp(-\frac{U}{k_B T}), \quad (2)$$

where k_B is the Boltzmann constant and U is the thermally activated energy of the flux flow. Thus $U(H)$ can be obtained from the slope of this linear part in the Arrhenius plot. The acquired $U(H)$ at various magnetic fields from 50 to 6000 Oe are summarized in Fig. 3(b). It is found that U is proportional to -ln$H$ (see the dashed line in Fig. 3(b)). Theoretically it was pointed out that [36, 37], the activation energy is determined by the free energy barriers to create a single free dislocation when the vortex translational correlation length is small enough. In this case, the logarithmic relationship can be expected. Thus our observations here strongly imply the 2D liquid state for the vortices.

With the increase of $1/T$, the resistance becomes constant, which is independent of temperature. Similar phenomena have been reported in other 2D SC systems and are considered as a hallmark of the quantum metallic state [19–23]. Such a metallic state in the vicinity of SC region could not be understood in the classic framework. Different theories have been proposed to interpret this dissipation in the low temperatures. Typically the different models can be distinguished by the magnetic field dependent behaviors of the saturated resistance at low temperatures. By considering the temperature-independent

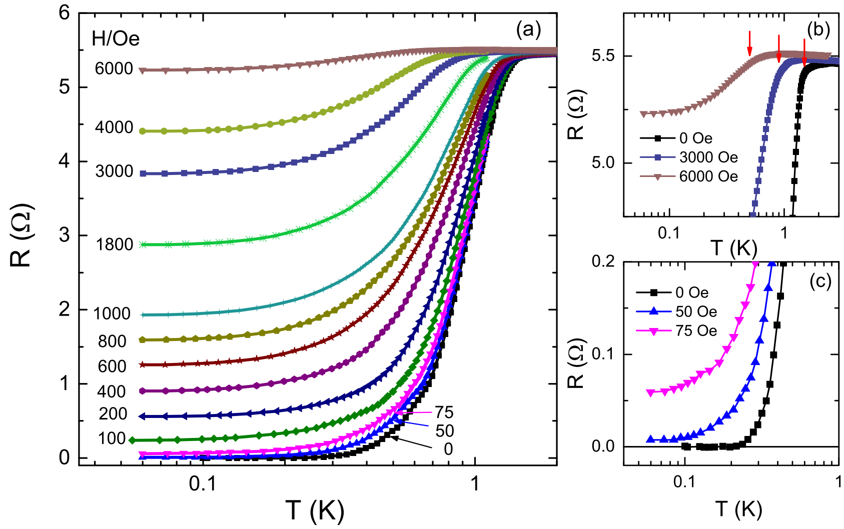

FIG. 2: (color online) (a) Electrical resistance as a function of temperature under the magnetic field up to 6000 Oe with $H//\text{c}$. (b, c) Enlarged view of the resistance data in the vicinity of onset transition points and zero-resistance region respectively. The red arrows in (b) indicate the onset transition points.

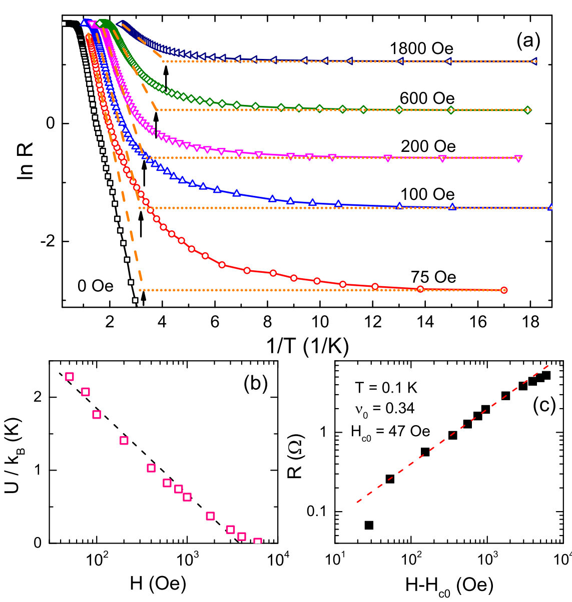

FIG. 3: (color online) (a) Arrhenius plots of longitudinal resistivity $\ln R$ vs $1/T$ at different fields. The data are shifted by 0.3 K^{-1} for clarity. The dashed lines are the fits with TAFF theory to the experimental data. The dotted horizontal lines are guides for eyes. The arrows indicates the transition points between the two regions with different behaviors. (b) The values of U at various magnetic field. (c) Magnetoresistance data at 0.1 K.

quantum tunneling of vortices, Shimshoni et al. predicted that the field induced increase of resistivity in the quantum metallic state should follow [38]

$$R \propto \exp[A(\frac{H}{H_{c2}} - 1)]. \quad (3)$$

On the other hand, a Bose metallic (BM) phase, where the interacting Cooper pairs form a gapless non-superfluid liquid, was also proposed [20, 39]. Based on this model, the unbinding of quantum dislocation-antidislocation pairs due to strong gauge field fluctuations will give rise to

$$R \propto (H - H_{c0})^{2\nu_0}, \quad (4)$$

where H_{c0} is the critical field for SC-BM transition. With a careful analysis, we found that Eq. (3) deviates seriously from the experimental data (not shown here). Meanwhile, Eq. (4) can describe the experimental results in a wide field range (see the red dashed line in Fig. 3(c)). The exponent ν is determined to be 0.34. The value of critical field H_{c0} (47 Oe) is quite reasonable, because the metallic state can be induced by the lowest field in our experiment, 50 Oe. The above analysis shows that the present system is more consistent with the theoretical model based on Bose metal.

Based on the above observations, we can draw the field-temperature phase diagram of the thin KV_3Sb_5, which is shown in Fig. 4. A true zero-resistance state is not observed under the lowest field of our experiment, 50 Oe. Thus we didn't indicate the SC region in this diagram. From the magnetoresistance data in Fig. 3(c), we found that the critical field for the SC-BM transition is 47 Oe at 0.1 K. This means indirectly that there may exist a very narrow SC region under low fields. Another remarkable

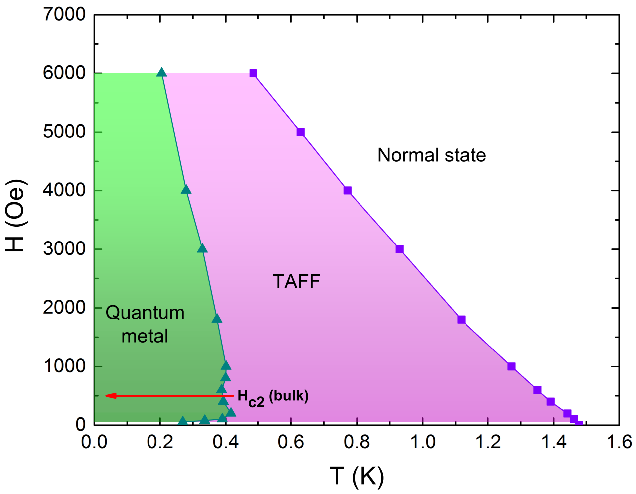

FIG. 4: (color online) Phase diagram for the KV_3Sb_5 thin film. The boundary between the TAFF and normal states is determined from the $R-T$ data using the criterion of 99% R_n. The boundary between the quantum metallic and TAFF states is determined by the black arrows shown in Fig. 3(a). The red arrow indicates the value of upper critical field for the bulk sample.

feature of this phase diagram is that the boundary between the quantum metallic and TAFF states is rather steep in a wide field range, revealing the robustness of the quantum metallic state against the magnetic field. Finally, we would like to point out that the upper critical field exceeds that of the bulk sample (see the red arrow in Fig. 4) by more than 10 times. The origin of the such unconventional observations, especially the possible correlation to the exotic electronic structure, is a very important topic for the theoretical realm in the future.

In summary, we successfully obtained the thin samples of the Kagome matal KV_3Sb_5 with the thickness down to 15 nm by using a mechanical exfoliation method. The dimensionality effect was observed in terms of the higher onset SC transition temperature, 2D-featured thermal activated energy, and the BKT-type resistance transition. Moreover, the upper critical field is enhanced by more than 10 times as compared with the bulk sample. The temperature-independent behavior of the resistance can be described by the model based on Bose metallic state. Our results provide a very unique and suitable platform to investigate the dimensionality effect in unconventional Kagome superconductors.

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