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We performed specific heat measurements of the superconducting single crystal of 2H-NbS_2 in the temperature range down to 0.6 K and magnetic fields up to 14 T. The temperature and magnetic field dependence of the electronic specific heat consistently indicate existence of two superconducting energy gaps in the system. The superconducting anisotropy depends on both temperature and magnetic field. Moreover, the angular dependence of the upper critical field deviates from the Ginzburg–Landau behavior and rather reminds that of MgB_2. All these features point to a multigap superconductivity in 2H-NbS_2. Our measurements are in a perfect agreement with the previous scanning tunneling spectroscopy of Guillamón et al.

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1. Introduction

The case of multiple electronic bands crossing the Fermi level can lead under certain circumstances to an interesting existence of multiple superconducting energy gaps in one system. The most spectacular example of this phenomenon is MgB_2 with different gaps in the three dimensional π-band and the 2D σ one. Superconducting dichalcogenides have also multiple bands at the Fermi energy but completely different symmetry and coupling among them than in MgB_2. Nevertheless, experimental indications are cumulating that two-gap superconductivity can be present also here.

2. Experimental

2H-NbS_2 single-crystal with the superconducting transition at $T_c = 6.05$ K was prepared as described elsewhere [1]. Crystal used for our measurements comes from the same batch as those studied previously by scanning tunneling microscopy (STM) [2].

The specific heat measurements were performed using an ac technique [3]. This method is based on applying periodically modulated power and measuring resulting temperature oscillations of the sample. Magnetization measurements were performed using a set of miniature GaAs-based quantum-well Hall sensors. Procedure of upper critical field (H_{c2}) determination by this method is described for example in [4].

3. Results

In Fig. 1a we present an effective superconducting anisotropy $\Gamma_{\rm eff}$ in the system (full symbols). This data were derived from measurements of the Sommerfeld coefficient γ (actually C/T at $T = 0.6$ K) for two perpendicular orientations of magnetic field with respect to the crystallographic structure of the sample (H parallel and perpendicular to the ab planes). Details and data can be found elsewhere [5]. The effective anisotropy $\Gamma_{\rm eff}$ is defined as a ratio of the fields applied in the two major crystallographic orientations corresponding to the same value of the Sommerfeld coefficient γ. Let us note that this $\Gamma_{\rm eff}$ tends towards the usual anisotropy of H_{c2}, $\Gamma = H_{c2}^{ab}/H_{c2}^{c}$ at large magnetic fields. As can be seen in Fig. 1a, $\Gamma_{\rm eff}$ is strongly field-dependent. The figure includes the curve obtained on MgB_2 (open symbols) for comparison [6]. In MgB_2 at low fields, the $\gamma(H)$ curves for the two principal directions are practically identical which gives $\Gamma_{\rm eff} = 1$. At larger fields, $\Gamma_{\rm eff}$ increases reflecting a reduced contribution from the isotropic π-band, reaching $\Gamma_{\rm eff} \approx 5$ which is the anisotropy of the σ-band dominant here. In NbS_2, one observes an opposite field dependence of $\Gamma_{\rm eff}$ which starts from a highly anisotropic value $\Gamma_{\rm eff} \approx 10$ at low fields and decreases to $\Gamma_{\rm eff} \approx 5.5$ at our maximum field.

A field dependent superconducting anisotropy is a typical signature of multigap superconductivity where a role of bands with different gaps can significantly vary with magnetic field [7]. In contrast to MgB_2, in NbS_2 both bands could be anisotropic, as suggested by analogy with $NbSe_2$ [8]. Moreover, anisotropy can be different in the two bands. This can explain a qualitatively different behavior of $\Gamma_{\rm eff}(H)$ in NbS_2 as compared to MgB_2

The superconducting anisotropy $\Gamma = H_{c2}^{ab}/H_{c2}^{c}$ is also temperature dependent in NbS_2, in contrast to one-gap superconductors where it is constant. The full circles in Fig. 1b represent evolution of the anisotropy of H_{c2}

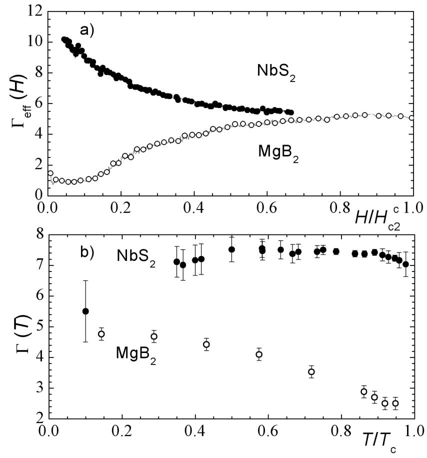

Fig. 1. Field (a) and temperature (b) dependence of the superconducting anisotropy (as defined in the text) in NbS$_2$ and MgB$_2$ (full and open symbols, respectively).

values derived from the temperature and the field-sweep measurements of specific heat; square is taken as an extrapolation of $\Gamma_{\rm eff}$ for $H/H_{c2} \to 1$ (see Fig. 1a). $\Gamma(T)$ of NbS$_2$ reveals again an opposite tendency compared to MgB$_2$ since it exhibits a decrease instead of an increase with decreasing temperature. Behavior of $\Gamma(T)$ results from a subtle balance between the Fermi velocities and the relative weights in the densities of states of the different bands. These precise calculations are still to be carried out in the case of NbS$_2$.

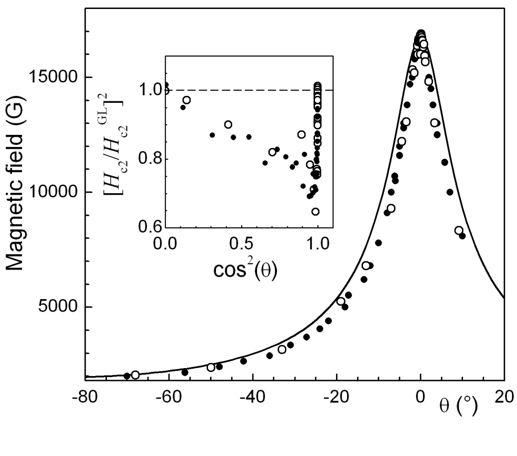

Fig. 2. Angular dependence of H_{c2} from specific heat (open symbols) and magnetization (full symbols) measurements. Line is the Ginzburg–Landau theoretical expectation for the single gap superconductor. Inset: ratio $[H_{c2}(\theta)/H_{c2}^{\rm GL}(\theta)]^2$ plotted as a function of $\cos^2\theta$.

Two-gap nature of NbS$_2$ is manifested also in anomalous angular dependence of H_{c2}. Figure 2 presents results of H_{c2} measured at $T = 5.5$ K at different angles θ between magnetic field and ab planes of the sample ($\theta = 0°$ for $H \parallel ab$ and 90° for $H \parallel c$) extracted from specific heat (open symbols) and magnetization (full symbols) measurements. For comparison we show theoretical Ginzburg–Landau behavior of H_{c2} (line) in the form of $H_{c2}^{\rm GL}(\theta) = H_{c2}^{ab}/\sqrt{\cos^2\theta + \Gamma^2\sin^2\theta}$ with parameters set to correspond to the data at the both extremes (at 0° and 90°). It is obvious from the figure that the observed behavior of H_{c2} deviates from that expected from the theory. The deviation is emphasized in the inset of Fig. 2 where the ratio $[H_{c2}(\theta)/H_{c2}^{\rm GL}(\theta)]^2$ is plotted as a function of $\cos^2\theta$. Similar tendency was observed also in the case of MgB$_2$ where it was proved to be related to the two-gap character of the system [9].

4. Conclusions

Our measurements presented here show a strong field and temperature dependence of the superconducting anisotropy of NbS$_2$. Moreover, the angular dependence of H_{c2} deviates from the GL theory in a similar manner as in MgB$_2$. This strongly supports previous result of the surface sensitive technique — scanning tunneling microscopy (STM), pointing to existence of two gaps in the system. Therefore, we conclude that NbS$_2$ is another example of a two-band superconductor.

Acknowledgments

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