Magnetic phase diagram of anisotropic superconductor 2H-NbSe$_2$


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Abstract

We report the magnetic phase diagram of a clean single crystal of 2H-NbSe$_2$ and present an update on the determination of its intrinsic superconducting parameters.

Keywords: Phase diagram; Reentrant peak effect; NbSe$_2$; Superconductivity

1. Introduction

The clean single crystals of transition metal chalcogenide 2H-NbSe$_2$ (superconducting $T_c(0) \approx 7.1$ K) are considered ideal for the study of intrinsic properties of Abrikosov flux line lattice (FLL) as the transverse and longitudinal correlation lengths - over which the triangular arrangement of the flux lines prevails - are of macroscopic order [1]. The Abrikosov FLL subject to fluctuations is expected to transform to flux liquid state near normal to superconductor phase boundary ($H_{c2}(T)$) at high fields; the FLL melting curve should move away from $H_{c2}(T)$ line and lie just above the $H_{c1}(T)$ line. A prerequisite [3] for the observation of melting curve as distinct from $H_{c2}(T)$ line (and its reentrant characteristic) in any system is the largeness of the value of its Ginzburg number, which is a measure of the ratio of thermal energy ($k_BT_c$) to superconducting condensation energy ($H_{c2}^2/8\pi$). 2H-NbSe$_2$ has an appreciable value ($\sim 10^{-4}$) of Ginzburg number, which lies in between high $T_c$ superconductors and conventional low $T_c$ alloys [1]. It is also a layered system for which anisotropic Ginzburg–Landau (GL) relationships are considered appropriate [3]. A quantitative comparison of experimental data with the theoretical predictions needs reliable values of superconducting parameters, like, coherence lengths $\xi_{a,c}$ and penetration depths $\lambda_{a,c}$, $\kappa_{a,c}$, etc. We present here an update [4] on the determination of the magnetic phase diagram in a clean single crystal of 2H-NbSe$_2$ for $H \parallel a$ and $H \parallel c$ via AC and DC magnetisation measurements and inter alia tabulate the revised values of $\xi_{a,c}, \lambda_{a,c}, \kappa_{a,c}$ at $T = 0$ and $t = T/T_c(0) = 0.97$.

2. Results and discussion

The phase diagram (see Fig. 1) comprises lower critical field lines $H_{c1}^{a,c}(T)$, the upper critical field lines $H_{c2}^{a,c}(T)$ and the peak effect (PE) lines $H_{p}^{a,c}(T)$. 

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The $H_{cl}(T)$ values have been determined using deviation from linearity criterion on the isothermal $4\pi M$ versus $H$ data recorded on a SQUID magnetometer and using a procedure described elsewhere [5]. The present values of $H_{cl}^{ac}(0)$ and $H_{cl}^{ac}(T)$ data fit to the relationship $H_{cl}^{ac}(0)(1 - T^2)^{1/2}$. The $H_{cl}^{ac}(T)$ values have been determined either by employing deviation from linearity criterion on isothermal normal state DC magnetisation response as the applied field values are lowered [5] or by identifying the temperatures of onset of the diamagnetic screening response in the in-phase AC susceptibility $x'(T)$ measurements. We find that near $T_c(0)$, the slope values $dH_{cl}^{ac}/dT$ are smaller than those at higher fields. Using literature values [1, 6] of $H_{cl}^{ac}(0)$ and the present values of $H_{cl}^{ac}(t = 0.97), H_{cl}^{ac}(0), H_{cl}^{ac}(t = 0.97)$, we have estimated, using GL relationships [3], the values of $\xi^{a,c}, \lambda^{a,c}, \kappa^{a,c}$ summarised in Table 1.

The $H_{cl}^{ac}(T)$ lines in Fig. 1 correspond to the temperatures of anomalous negative peaks in $x'(T)$ data recorded at fixed $H$ (see Fig. 2). The negative peak in a $x'(T)$ curve is a consequence of ubiquitous PE phenomenon in a weakly pinned FLL and is considered a fingerprint of collapse of its shear modulus [1]. The $H_{cl}^{ac}(T)$ curves track the respective $H_{c2}^{ac}(T)$ curves from high $H$ down to 200 Oe. However, at about 150 Oe, a turn around characteristic ($dT/dH > 0$ for $H < 150$ Oe) develops [4] and such a behaviour is strikingly similar to the predicted reentrant characteristic in the melting curve of a pure FLL [2, 3]. The intervortex spacing $a_0(a_0^2 = 2A_0/\sqrt{3}^B)$ at

![Graph showing magnetic phase diagram of 2H-NbSe$_2$.]

**Fig. 1.** Magnetic phase diagram of 2H-NbSe$_2$.

![Graph showing $\chi'(T)$ curves of a frequency of 211 Hz showing peak effect phenomenon for $H || c$ and $H || a$ in 2H-NbSe$_2$.]

**Fig. 2.** $\chi'(T)$ curves of a frequency of 211 Hz showing peak effect phenomenon for $H || c$ and $H || a$ in 2H-NbSe$_2$.

<table>
<thead>
<tr>
<th>$T/T_c(0)$</th>
<th>$H_{c2}^{ac}$ (kOe)</th>
<th>$H_{cl}^{ac}$ (kOe)</th>
<th>$\xi^{a,c}$ (Å)</th>
<th>$\lambda^{a,c}$ (Å)</th>
<th>$\kappa^{a,c}$ (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>145.56</td>
<td>128.380</td>
<td>77.27</td>
<td>1065.450</td>
<td>49.14</td>
</tr>
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<td>0.97</td>
<td>1.51, 0.745</td>
<td>18.27</td>
<td>666.328</td>
<td>3055.6830</td>
<td>10.46</td>
</tr>
</tbody>
</table>

**Table 1.** Intrinsic superconducting parameters of 2H-NbSe$_2$
The observed broadening of negative peak in $\chi'$ and its eventual disappearance at low $H(< 50 \text{ Oe})$ is believed to be a consequence of the crossover from interaction-dominated regime to disorder-dominated regime as $\alpha_0$ exceeds $\lambda$ values [4]. This speculation stands confirmed [7] from new data in an impure crystal of 2H-NbSe$_2$, where broadening of peak in $\chi'$ sets in below about 400 Oe and the reentrant characteristic in PE curve becomes elusive.

References