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Abstract

$NbSe_2$ shows coexistence of a charge density wave (T_{CDW} ∼32K) with a superconducting state below T=7.2K. Recent ARPES measurements revealed different values of the superconducting gap on the main sheets of the Fermi Surface. These results suggest a multigap superconductivity such as in MgB_2. The temperature dependence of the magnetic penetration depth ($\lambda(T)$ down to $T_c/16$ has been measured on high quality single crystals in the Meissner state. A strong increase of the in-plane penetration depth is observed, signaling the presence of low lying excitations. Given the relative contributions of each Fermi surface sheet, these measurements indicate that a reduced gap is not necessarily only found on the small Se sheet as suggested by the ARPES measurements. These results are discussed in a framework of multigap superconductivity.

Key words: $NbSe_2$, penetration depth, superfluid density
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The hexagonal dichalcogenides $NbSe_2$ has attracted a large interest in the last few decades for the coexistence of an incommensurate charge density wave with a superconducting state below T_c=7.1K [1]. Furthermore, the superconducting state shows unusual properties, which can not be explained by an isotropic BCS weak coupling model. For example, the electronic specific heat has already shown the presence of a reduced energy gap [2]. Recently, $NbSe_2$ has been revisited in the light of multigap superconductivity. ARPES measurement suggested that the low energy excitation gap is due to the Se p-band which has a small electron-phonon coupling constant [3]. A directional probe combined to the particular anisotropy of the Fermi Surface of $NbSe_2$ allows us to test the excitation gap on the different sheets.

In this paper, we present high sensitivity measurements of the change of the in plane and c-axis temperature dependence of the magnetic penetration depth in the Meissner state (respectively $\Delta\lambda_a$ and $\Delta\lambda_c$). The detailed results are published elsewhere [4].

1. Experimental method

$\Delta\lambda_i$ (i=a or c) was measured with a LC circuit driven by a tunnel diode operating at 14MHz. The very low AC field probe (∼10μT) and the screening of any DC magnetic field ensured that the sample was kept in the Meissner state. The frequency shift of the LC oscillator is directly proportional to $\Delta\lambda$.

Single crystals from three sources (Lausanne,

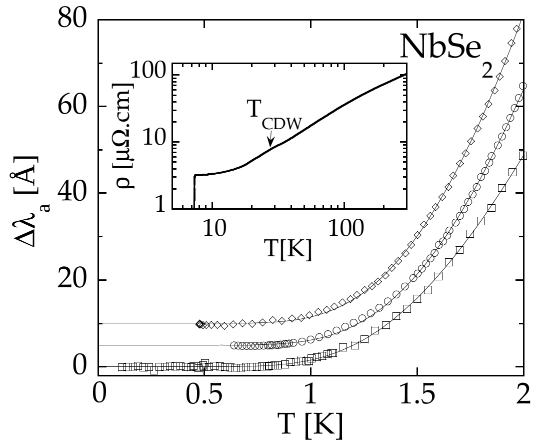

Fig. 1. Temperature dependence of the in-plane penetration depth for samples from different sources (measured at Bristol □, Grenoble ○, Urbana ◇). The field configuration is H||c for Bristol's samples with an aspect ratio of 40. The contribution from the c-axis is negligible. For the other sample H is perpendicular to the c-axis. For clarity the data are offset. The lines are a fit with a superconducting gap of Δ=1.1$\pm kT_c$. Inset, temperature dependence of the in plane resistivity for a single crystal from the same batch as Grenoble's samples.

Tsukuba, Bell Lab) have been measured in three different laboratories (Grenoble, Bristol, Urabana Champain respectively). Crystals of thickness t were grown with large flat layers perpendicular to the c-axis . Each side of the samples were cut. Samples from different batches have a RRR between 33 and 70 (see inset fig. 1). No drastic change with sample quality has been observed.

When the magnetic field is applied along the c-axis, the supercurrents are flowing only in the basal plane. However, for a magnetic field applied perpendicular to the basal plane, both, a and c-axis directions are probed. For a sample of rectangular shape with a section ($\perp H$) of width w and thickness t, the frequency shift is proportional to $\Delta\lambda_a + \frac{t}{w}\Delta\lambda_c$. To extract the out-of plane penetration depth the aspect ratio of a sample is changed by cutting.

2. Results

In fig. 1 the low temperature dependence of the in-plane penetration depth is shown. All the curves are fitted with the approximated expression (valid for $kT < T_c/3$):

$$\Delta\lambda_i(T) \simeq \lambda_i(0)\sqrt{\frac{\pi\Delta_0}{2T}}\exp\left(-\frac{\Delta_0}{T}\right) \qquad (1)$$

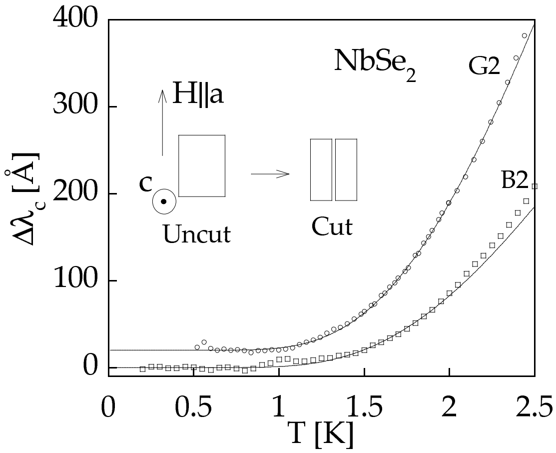

Fig. 2. Temperature dependence of the out-plane penetration depth calculated from a change of the aspect ratio (see text) (B2 measured at Bristol, G2 data from Grenoble is offset).

where Δ_0 is the superconducting gap at $T = 0$K. We find Δ_0=1.1$\pm$0.1kT_c, less than the value expected for a weak coupling BCS gap ($\sim$1.76kT_c). In fig. 2 the low temperature dependence of the c-axis penetration depth is fitted for $T < 2$K with the same expression. A gap of $\Delta_0 = 1.3 \pm 0.1kT_c$ is measured.

The experimental results have to be compared with the calculated Fermi surface. The Fermi surface of $NbSe_2$ is formed of 2 cylinders along the c-axis from the 4d-electrons of the Nb and also a small flat pancake around the center of the Brillouin zone from the p-electron of the Se. This sheet contributes only to 2% to the total in-plane superfluidity but 85% to the out-plane superfluidity [5]. So the reduced energy gap measured by in-plane penetration depth is on one or more of the quasi-2D Nb sheets. Moreover, $\Delta\lambda_c$ shows that the superconducting gap associated to the Se sheet is not smaller than the smallest gap of the quasi-2D Nb band. These results are in strong contrast with previous measurements [3].

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