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Anisotropic behaviour of transmission through thin superconducting NbN film in parallel magnetic field

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ABSTRACT

Transmission of terahertz waves through a thin layer of the superconductor NbN deposited on an anisotropic R-cut sapphire substrate is studied as a function of temperature in a magnetic field oriented parallel with the sample. A significant difference is found between transmitted intensities of beams linearly polarised parallel with and perpendicular to the direction of applied magnetic field.

1. Introduction

Far-infrared techniques provide valuable information about condensate, quasiparticle and vortex behaviour in both equilibrium and non-equilibrium states of superconductors [1]. Magnetic fields substantially change the properties of superconductors in two different ways: by pair-breaking mechanism or by introducing a vortex lattice. Regarding mutual orientation of applied magnetic field, sample position and linear polarisation, three fundamental configurations of magneto-optical experiments can be recognised, as illustrated in Fig. 1. While in the *Faraday geometry*, optical properties are insensitive to the direction of the incident beam linear polarisation, in the *Voigt geometry*, the dependence is generally possible.

As the case of Faraday geometry is better understood [2–4] and only few studies deal with the parallel field [5–7], in this work we concentrate on transmission in Voigt geometry. Very thin superconducting films of thickness, d, lower or comparable with the coherence length, ξ, exhibit in parallel magnetic field a vortex free state [5]. In thicker films, vortices are introduced inside the film. Luzhbin [6] found that in such a geometrically frustrated system vortices arrange themselves in rows.

In this paper, we describe transmission of monochromatic THz radiation with well-defined linear polarisation through a thin NbN film with magnetic field applied parallel to its surface. Anisotropy of transmission can be regarded as a sign of vortex presence.

2. Experiment

The superconducting NbN film of nominal thickness $d_1 = 15$ nm was grown epitaxially on an anisotropic R-cut sapphire substrate (with the c-axis at angle $\varphi = 57.6^\circ$ with respect to the surface normal), see Table 1. This sample has already been studied by us in zero magnetic field [8].

Our optically pumped far-infrared laser produces several discrete lines in the range from 0.4 to 4.9 THz. Intensity of transmitted beam through the sample placed inside magneto-optical cryostat is measured by a helium cooled bolometer and relative transmission is evaluated as a ratio between measured transmission and transmission measured just above T_c. Our experimental protocol is to set a constant magnetic field and to cool the sample from slightly above T_c to the minimum attainable temperature (usually 3 K); then the sample is heated up. Temperature of the sample is monitored by a small Cernox thermometer located nearby, which performs well even in high magnetic fields. The DC resistivity is monitored simultaneously, by the four-probe measurement method. Further details can be found elsewhere [9].

Utilising the wire-grid polarisator the transmission is measured for two fundamentally different linear polarisations (see Fig. 1), polarisation parallel with ($E^{\parallel}$) and perpendicular to ($E^{\perp}$) the applied magnetic field. In our special case, the angle between the electric

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Table 1
Parameters of the sample.

Film	d_1 [nm]	T_c [K]	$\sigma_N(0)$ $\Omega^{-1}.m^{-1}$	Substrate	d_2 [mm]
NbN	15	16	0.51×10^6	Al_2O_3	0.33

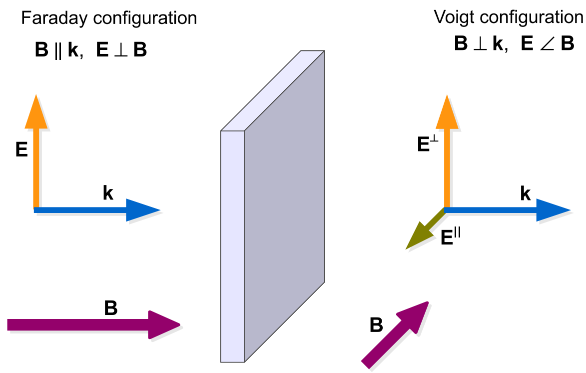

Fig. 1. Schematics of fundamental magneto-optical geometries: $\vec{B}$ is a static external magnetic field, $\vec{k}$ is a wavevector and $\vec{E}$ denotes electric field of an incoming beam.

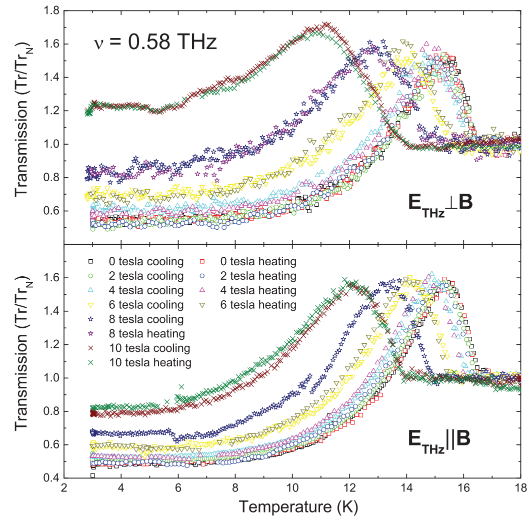

Fig. 2. Temperature dependence of transmission through NbN thin film at 0.58 THz in parallel magnetic fields up to 10 T. Upper panel: perpendicular polarisation $E^{\perp}$; lower panel: parallel polarisation $E^{\parallel}$.

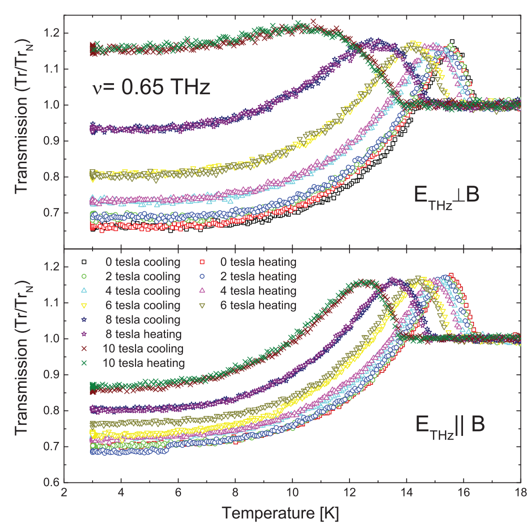

Fig. 3. Temperature dependence of transmission through NbN thin film at 0.65 THz in parallel magnetic fields up to 10 T. Upper panel: perpendicular polarisation $E^{\perp}$; lower panel: parallel polarisation $E^{\parallel}$.

vector of the incident beam and the extraordinary ray axis of the birefringent sapphire substrate is 45°, therefore the relative transmissions of the parallely and perpendicularly polarised radiations should be equal in zero magnetic field. Note, however, that the intensities of the parallely and perpendicularly polarised rays are different, which might affect the accuracy of the individual measurements, but resulting dependencies are reliable.

3. Theoretical model

Zero magnetic field conductivity $\tilde{\sigma}_s$ is well described by the BCS theory-based Zimmermann model [10]. In our model, vortices are considered as cylindrical inclusions of normal state material [11]. Their typical radius is proportional to the coherence length ($\xi \cong 5$ nm for NbN at zero temperature) which is much smaller than the typical wavelengths in the terahertz range. We can use the long wavelength limit when electromagnetic radiation does not sense individual vortices and the system can be thought of as a homogeneous one, possessing an effective complex conductivity $\tilde{\sigma}_{eff}$ which strongly depends on the volume fraction of vortex cores $f_n = V_n/V$ and the superconducting fraction $f_s = 1 - f_n$.

In our case, vortices are considered as inclusions and the superconducting environment surrounding the vortices as a filler. Maxwell–Garnett formulated his theory [12] for dilute systems assuming that inclusions feel the external field that coincide with the local field inside the filler. In contrast with the Bruggeman theory [13], this model respects the topology of the vortex system. Mutual interaction between inclusions is neglected. More generally, MGT formulas can hold even for higher concentrations of inclusions as long as the filler is percolated [14]. Considering the special case of cylindrical inclusions, MGT gives

$$\tilde{\sigma}^{\perp}_{MGT} = \frac{2 f_n \tilde{\sigma}_s (\tilde{\sigma}_n - \tilde{\sigma}_s)}{(1 - f_n)(\tilde{\sigma}_n - \tilde{\sigma}_s) + 2\tilde{\sigma}_s} + \tilde{\sigma}_s \; ; \quad (1)$$

$$\tilde{\sigma}^{\parallel}_{MGT} = f_n \tilde{\sigma}_n + (1 - f_n)\tilde{\sigma}_s \; , \quad (2)$$

for electric fields perpendicular to and parallel with the vortex axes, respectively. The latter formula can be qualitatively understood assuming that charges along the vortex cores and in the superconducting matrix move independently.

4. Results

Let us describe our experimental results. Transmission is measured at frequencies 2.52, 0.65, 0.58, 0.53 and 0.40 THz.

Zero-field transmission has been measured in both polarisations. The observed difference does not exceed 5%, which most likely can be attributed to a slight misalignment of the sample. Importantly, one can appreciate good agreement between transmission obtained while cooling and heating our sample. The transmission curves differ due to frequency dependence of the complex conductivity and interference effects. Detailed analysis of zero-field transmission [8] and interpretation [15] was reported in our previous studies.

We study differences between the transmission for $E^{\perp}$ and $E^{\parallel}$ with increasing magnetic field. In low magnetic fields up to 2 T, the measured transmission deviates from the zero field values only slightly, usually within the experimental error. In large magnetic fields, we observed frequency dependent anisotropic behaviour of transmission. Significant differences are observed in the case of 0.58 THz (Fig. 2) and 0.65 THz (Fig. 3) lines, while for the remaining laser lines anisotropy is less pronounced (see Appendix).

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