Infrared studies of superconducting MgB_2 thin films

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Abstract

Reflectance of superconducting MgB_2 thin films ($T_c \approx 35$ K) has been measured in a broad spectral range from 30 to 110 000 cm^{-1}. A typical plasma edge with a reflectance minimum at 15000 cm^{-1} has been found. In the far-infrared region we observe a pronounced rise of the reflectance below 60 cm^{-1}, which appears below T_c and can be associated with superconducting state. The temperature-dependent complex conductivity at infrared frequencies has been determined. The real and imaginary parts of the conductivity below T_c show a temperature evolution, which is characteristic for superconducting gap opening (decrease in σ_1 and rise in σ_2).

Key words: MgB_2; superconductivity; optical properties;

The recent discovery of superconductivity in MgB_2 with relatively high $T_c \approx 39$ K has started an intensive effort to understand the mechanism of superconductivity in this material. Several mechanisms have been proposed, but the isotope effect and light atomic masses, both enhancing the phonon frequencies, suggest phonon-mediated (BCS) superconductivity. High T_c and anomalous magnitude of coupling constant $\lambda \sim 1$ indicate a strong coupling Eliashberg version of BCS theory.

Optical measurements are known to be a powerful tool for investigating important physical quantities such as the gap 2Δ, scattering rate $1/\tau$, and plasma frequency ω_p. Several attempts[1–4] have been undertaken to determine them, but their values obtained by experiments are distinctly different (e.g. 2Δ from 3 to 16 meV). Other probes as tunneling and photoemission also provide various results. Therefore, the current state of understanding of the superconductivity in MgB_2 is inconclusive.

In this work we study optical reflectance $R(\omega)$ in a broad spectral range, temperature dependent infrared conductivity $\tilde{\sigma}(\omega) = \sigma_1(\omega) + i\sigma_2(\omega)$ and DC conductivity of MgB_2 films deposited on c-cut Al_2O_3, Si and Si/NbN substrates.

The samples are mounted in a cryostat to measure the temperature dependent infrared reflectance at near-normal incidence using a Bruker 113v spectrometer. The spectrometers Shimadzu UV-1601 and Beaudouin MVR-100 are used to cover the spectral range up to 110000 cm^{-1} at room temperature. The absolute value of reflectance is determined as a ratio of the sample and Al mirror spectra. The reflectance in the visible spectral range is compared with data obtained by a Woollam spectroscopic ellipsometer. The infrared conductivity is evaluated using the Kramers-Kronig analysis of the reflectance.

MgB_2 thin films on Al_2O_3, Si and Si/NbN substrates are prepared[6] by either vacuum co-deposition of boron and magnesium, or high-temperature magnesium annealing of boron films . The first type of them are prepared on Al_2O_3, Si and Si/NbN substrates, by vacuum co-deposition of Mg-B precursors with the nominal thickness of about 300 nm and an

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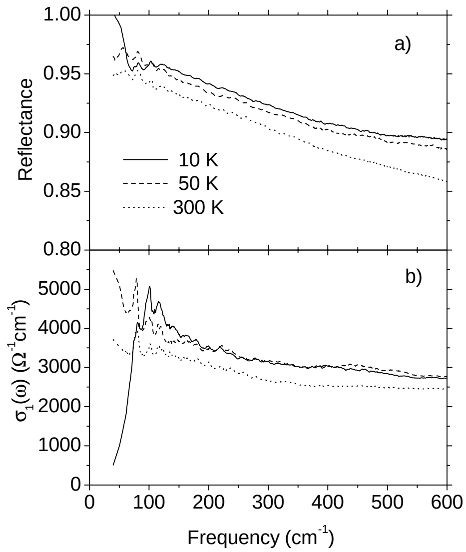

Fig. 1. The temperature dependent infrared spectra of a MgB_2 film on Al_2O_3 from 30 to 600 cm^{-1}: a) reflectance, b) real part of conductivity.

ex-situ annealing process in Ar atmosphere at 600 ^{o}C within 15 minutes. The resulting MgB_2 films were amorphous with the maximal onset of superconductivity (on NbN/Si substrates only) at $T_{con} \approx 38$ K and transition width of 1 K.

The second type films are prepared on unheated single crystal Al_2O_3 substrates, by thermal evaporation of boron and, subsequently, enclosed in a Nb tube together with Mg chips. The Nb tube is placed in an annular furnace and kept in Ar atmosphere at the pressure p $\sim$ 3 kPa. The furnace temperature is then increased from room temperature to 800 ^{o}C in 60 minutes, kept there for 30 minutes, and quenched back to room temperature in five minutes. The films are rough, polycrystalline with 1 μm single-crystal blocks. The best thin films were characterized by $T_{con} \approx 39$ K and the width of below 1 K. DC resistivity decreases by a factor 3.6 on cooling from room temperature to T_c.

The measured films were not transparent in the used spectral range from 30 to 110000 cm^{-1}. Their reflectivity shows a minimum at 15000 cm^{-1} for the films on Al_2O_3, which is shifted to 18000 cm^{-1} and becomes less pronounced for the films on NbN/Si. The reflectance does not follow exactly the Drude model in the entire spectral range. A better agreement with the model is obtained for the sample on Al_2O_3 with parameters: plasma frequency $\omega_{p,D}$=25500 cm^{-1}, scattering rate γ=4800 cm^{-1} and ϵ_∞=3.5. The values are overestimated in respect to literature[3–5]. Our reflectance is about 8% lower than the published data[3], where another band is found at 18000 cm^{-1}. The authors do not observe the minimum close to plasma edge. The difference between the Drude model and our experimental data, and large value for $\omega_{p,D}$ and γ could be due to a diffusion scattering from the surface roughness of our samples.

The infrared spectra at selected temperatures for the MgB_2 film deposited on the Al_2O_3 substrate are presented in Fig. 1. The normal state reflectance in Fig. 1a increases in the whole spectral range as temperature decreases from 300 to 50 K. As the temperature drops below T_c a reflectance rise up to the value 1 appears in the low-frequency part of the spectrum. It starts below 60 cm^{-1} for the lowest temperature T=10 K and it shifts down to 40 cm^{-1} for T=25 K, which is not shown in the figure. This behavior is similar to what has been observed by some authors[1,5] and we also interpret it as a direct observation of the superconducting gap. The real part of conductivity in Fig. 1b calculated by Kramers-Kronig analysis behaves in the way (sharp decrease), that supports this idea. The infrared measurements performed by Tu *et al.*[3] reveal a higher level of reflectance than our data and, therefore, also conductivity. On the other hand, their conductivity decrease in low-frequency region is spread over much broader frequency interval. It cannot be associated with the gap and behaves similarly to high-T_c cuprates. The noise in our spectra, caused probably by the surface roughness, prevent us to study a fine structure of the gap. However, we still believe that our measurement demonstrates gap opening at about 50 cm^{-1} (6 meV).

The data from tunneling spectroscopy exhibit two distinct superconducting energy gaps with $\Delta_S(0)$=2.8 meV and $\Delta_L(0)$=7 meV [7], however the multi-band model presented by Liu at al. [8], where both the 2-dimensional and 3-dimensional Fermi surfaces contributing to superconductivity, can not be excluded [9]. The large gap is in reasonable agreement with our value.

In conclusion, we have measured reflectance in broad spectral range and calculated infrared conductivity of MgB_2 films. In our spectra, we can observe features that indicate opening of superconducting gap at 6 meV.

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