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 $\sigma_1$ and rise in $\sigma_2$).

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 $2\Delta$, scattering rate $1/\tau$, and plasma frequency $\omega_p$. Several attempts[1–4] have been undertaken to determine them, but their values obtained by experiments are distinctly different (e.g. $2\Delta$ 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$_2$O$_3$, 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$_2$O$_3$, 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$_2$O$_3$, Si and Si/NbN substrates, by vacuum co-deposition of Mg-B precursors with the nominal thickness of about 300 nm and an
ex-situ annealing process in Ar atmosphere at 600 °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$_2$O$_3$ substrates, by thermal evaporation of boron and, subsequently, enclosed in a Nb tube together with Mg chips. The Nb tube is placed in an an- nular furnace and kept in Ar atmosphere at the pressure $p \sim$ 3 kPa. The furnace temperature is then increased from room temperature to 800 °C in 60 minutes, kept there for 30 minutes, and quenched back to room temperature in five minutes. The films are rough, polycrystalline with $1 \mu$m 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 sample on Al$_2$O$_3$ with parameters: plasma frequency $\omega_{p,D} = 25500$ cm$^{-1}$, scattering rate $\gamma = 4800$ cm$^{-1}$ and $\epsilon_{\infty} = 3.5$. 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 $\gamma$ 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$_2$O$_3$ 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 $\Delta(0) = 2.8$ 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.

References