Microwave measurement of energy gap and penetration depth of MgB_2 thin film

B.B. Jin [a,*], N. Klein [a], A. Pimenov [b], A. Loidl [b], S.I. Krasnosvobodtsev [c], W.N. Kang [d], Hyeong-Jin Kim [d], Eun-Mi Choi [d], Sung-IK Lee [d]

[a] *ISG-2, Forschungszentrum Jülich, Institute of Thin Films and Interfaces, D-52425 Jülich, Germany*
[b] *Universität Augsburg, Experimentalphysik V, EKM, 86135 Augsburg, Germany*
[c] *P.N. LebedevPhysics Institute, Russian Academy of Sciences, 117924 Moscow, Russia*
[d] *National Creative Research Initative Center for Superconductivity, Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea*

1. Introduction

The recent discovery of superconductivity at 39 K in MgB_2 has generated a great deal of interest because it is believed to be the highest critical temperature for binary non-copper-oxide materials [1]. Intense efforts have been undertaken to investigate the electrodynamic properties of this new material, which may help to distinguish between different physical pictures concerning the energy gap [2–6]. One important quantity is the magnetic penetration depth λ, which is inversely proportional to the square root of the superfluid density [7]. For a conventional s-wave pairing state the energy gap in the excitation spectrum manifests itself in an exponential temperature dependence of λ. However, for d-wave superconductivity such as appearing in high-T_c material, the temperature dependence of λ is linear due to the presence of nodes in the gap function [8]. If impurity scattering is considered the temperature dependence of λ can change from T to T^2. Microwave measurements are commonly considered

* Corresponding author. Fax: +49-2461-612470.
E-mail address: b.b.jin@fz-juelich.de (B.B. Jin).

as an effective and sensitive method to determine the temperature dependence of λ. In this paper we report about measurements of the temperature dependence of λ of two MgB_2 thin film employing a dielectric resonator technique by measuring small changes of resonant frequency f_r with temperature [9]. The results show that the change of λ is exponential with temperature in the low temperature region, which implies a finite energy gap with s-wave symmetry.

2. Results and discussion

Two pieces of MgB_2 thin film were used in our measurements. They were prepared by a Russian group (sample A) and a Korean group (sample B). The films were deposited on plane parallel [1 1 0 2] oriented sapphire substrates [10,11]. Sample A exhibits a sharp superconducting transition at $T_c = 32$ K. The thickness is about 600 nm. Sample B has a zero-resistance temperature of 37.5 K with a thickness of about 400 nm. The detailed procedures of preparing the films can be found in Ref. [10,11]. The dielectric (sapphire) resonator technique is used to measure the temperature dependence of change of λ [9]. The cavity with part of one endplate replaced by the thin film sample was excited in the $TE_{01\delta}$-mode (about 18 GHz in our case) under weak coupling conditions. Two sample holders, which have different diameters for the holes in the centre, are employed for two sizes of the substrates. The area of the film under investigation exposed to the rf fields of the resonator corresponds to a geometric factor of 740 and 638 Ω, respectively. The temperature dependence of the change of penetration depth $\delta\lambda$ was determined from the temperature dependence of the resonant frequency $f(T)$ using

$$\delta\lambda = \frac{G}{\pi\mu_0}\frac{f(T) - f(4.2\ \mathrm{K})}{f^2(4.2\ \mathrm{K})} \tag{1}$$

with $\mu_0 = 1.256 \times 10^{-6}$ V s/A m. Applied correction with respect to a finite film thickness are explained in Ref. [6]. The contributions from the thermal expansions of copper cavity and of the dielectric puck and from the change of skin depth of the copper cavity, called background contribution, can be neglected. In order to verify the validity of this assumption we measured the resonant frequency dependence on temperature employing a copper sample. In this case the frequency change is caused by background contribution plus the skin depth change of the copper sample. Therefore, it should be higher than the background contribution. Fig. 1 depicts the frequency change dependence on temperature for the copper sample and a MgB_2 film (sample A) for comparison. For clarity the inset shows the comparison below 20 K. From Fig. 1 we conclude that the background contribution is much less than the frequency change of the MgB_2 thin films due to temperature changes of λ. We can also estimate the background contribution from the measurement. When the temperature changes from 4 to 10 K, the change of f_r is 1.35 kHz. According to Eq. (1) the corresponding change of penetration depth is about 0.8 nm. When the temperature changes from 4.2 to 20 K the f_r change is about 4.4 kHz corresponding to a change of λ by 2.5 nm. These values are much smaller than that for MgB_2 films in the same temperature regions except in the temperature region close to 4.2 K. Therefore, Eq. (1) was applied directly and the small system errors are ignored.

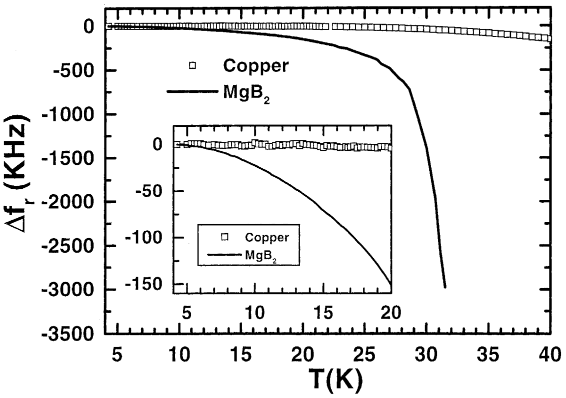

Fig. 1. Change of f_r vs temperature (4.2–40 K) when the sample is copper and MgB_2, respectively. For clarity the inset show f_r change from 4.2 to 20 K.

Fig. 2 shows the temperature dependence of $\delta\lambda$ up to T_c. Here $\delta\lambda$ is defined as $\lambda(\mathrm{K}) - \lambda(4.2\ \mathrm{K})$. Fig. 3 shows the temperature dependence of $\delta\lambda$ in the low temperature region. The symbols represent the experimental results and lines represent the

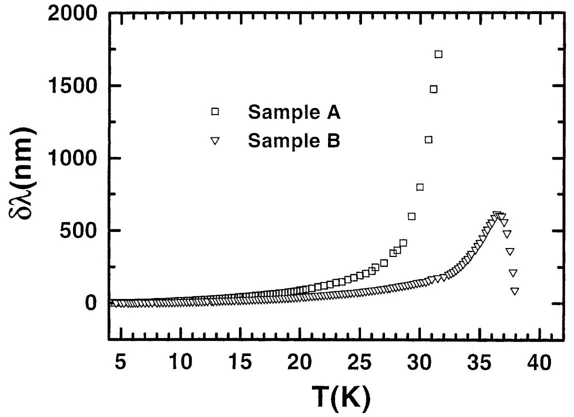

Fig. 2. The temperature dependence of $\delta\lambda$ of two MgB_2 thin films.

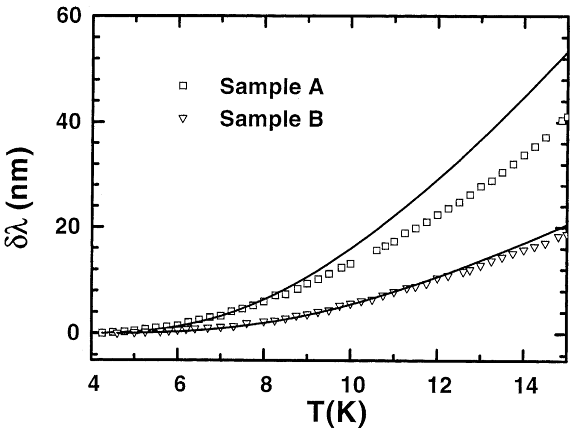

Fig. 3. The temperature dependence of $\delta\lambda$ in the low temperature region. The lines represent the exponential fit to the measurements.

exponential fitting. According to our analysis an exponential temperature dependence is valid below about $T_c/4$. The fitting parameters of Δ/kT_c and λ_0 are 1.25 and 290 nm for sample A and 1.20 and 165 nm for sample B. Since we obtain the Δ/kT_c and λ values by fitting procedures it is necessary to know how sensitive the fit is to the changes of the fitting parameters. Fig. 4 shows the $\delta\lambda$ dependence on temperature with different Δ/kT_c and λ_0 for sample A. When Δ/kT_c and λ deviate by 0.1 and 20 nm from the fit values the fitting curves obviously deviate from the experimental results. Therefore, we can conclude that the tolerances of Δ/kT_c and λ_0 are <0.1 and 20 nm, respectively. In the temperature

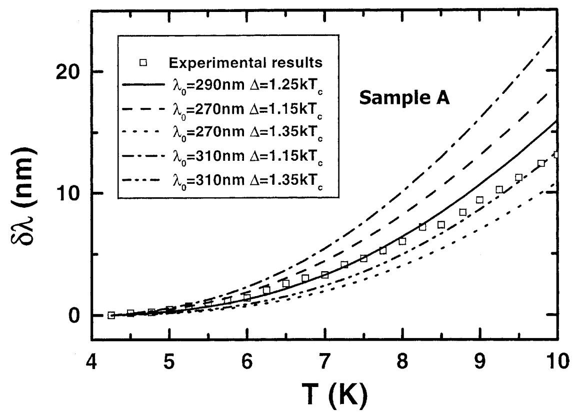

Fig. 4. The sensitive analysis of Δ/kT_c and λ_0 for sample A.

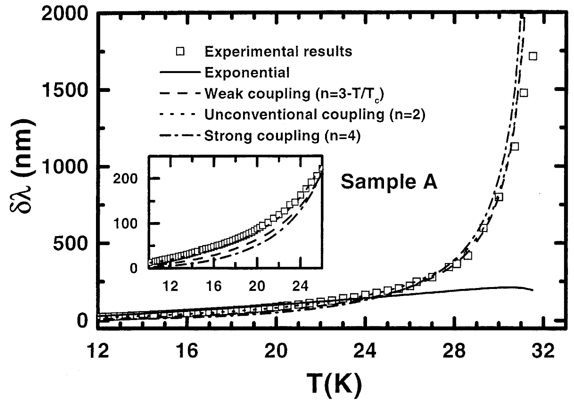

Fig. 5. Comparisons of the fits above $T_c/2$ using an analytical approximation $\lambda(T) = \lambda_0/[1-(T/T_c)^n]^{1/2}$ with different values of the power index n. For clarity the inset show a comparison below 26 K.

region above $T_c/2$ the temperature dependence of λ can be described by an analytical approximation $\lambda(T) = \lambda_0/[1-(T/T_c)^n]^{1/2}$ with different values of the power index n [7]. The different n corresponds to different mechanisms. The fitting curves with different n are depicted in Fig. 5. The inset shows experimental result and fitting curve below 26 K. From the figure we find $n = 2$ gives the best fit.

3. Summary

We measured the $\delta\lambda$ dependence on temperature with dielectric resonator technique. The results show the exponential dependence on temperature at low temperature region. It suggests that a finite gap exists in all directions of the Fermi surface. The values of energy gap for two samples are 3.3 and 3.8 meV.

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