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Effect of thermal expansion in microwave conductivity measurement

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Abstract

Systematic investigation was performed experimentally on the effect of the thermal expansion of the samples in the microwave-surface-impedance measurement by the resonant technique, using conventional superconductors, Pb and Nb, with various sample sizes. The measurement of the surface reactance, X_S, was found to be very sensitive to the thermal expansion, whereas that of the surface resistance, R_S, was insensitive. We propose a new relation between the measured experimental data and the surface impedance, to deal with this problem. We also propose a quantity which represents the degree of the thermal expansion in the microwave measurement.

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Keywords: Microwave; Thermal expansion; Surface impedance; Resonant technique; Cavity perturbation technique

1. Introduction

Microwave surface impedance, $Z_S = R_S - iX_S$, of a superconductor has played a significant role in investigating superconducting properties, such as the penetration depth, the quasiparticle conductivity, and the vortex dynamics [1–3]. For the measurement of Z_S, cavity perturbation technique [4] is used very often. In this technique, one measures the change of the inverse of the quality factor, Q, $\Delta(1/2Q)$, and that of the center frequency of the resonance, f, $-\Delta f/f$, caused by the insertion of the sample into the resonator. For metallic

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samples, they are related to R_S and X_S, respectively, as follows:

$$\Delta\left(\frac{1}{2Q}\right) = \frac{R_S}{G}, \tag{1a}$$

$$-\frac{\Delta f}{f} = \frac{X_S - C}{G}, \tag{1b}$$

where G is the geometrical factor and C is the metallic shift which is the frequency shift caused by the insertion of a perfect conductor with the same volume as the sample. This relation can be understood physically as follows. The Q represents the degree of the energy dissipation and f represents the effective space that microwave electromagnetic field can spread out. Indeed, $X_S = \mu\omega\delta/2$ for a normal metal, and $X_S = \mu\omega\lambda$ for a superconductor, where δ and λ are the skin depth and the penetration depth of the sample, respectively, ω is the angler frequency, and μ is the permeability of the sample. For materials of interest in this paper, μ can be regarded as the permeability of vacuum, μ_0. In the analysis of the experimental data, G and C are usually considered to be constants, and determined by the DC resistivity, ρ_{DC}, utilizing the relation,

$$R_S = X_S = (\mu_0\omega\rho_{DC}/2)^{1/2}. \tag{2}$$

This is satisfied when the frequency is much lower than τ^{-1}, where τ is the scattering time of the quasiparticle, and the electromagnetic response can be regarded as local. However, C cannot be regarded as temperature independent and the analysis described above is not valid, particularly when the thermal expansion of the sample is not negligible compared with the change of δ or λ. Thus, the accurate measurement of X_S is very sensitive to the thermal expansion of the sample.

Thermal expansion was studied by measuring f in the cavity perturbation technique in quasi one-dimensional organic materials [5,6]. To our knowledge, however, the effect of thermal expansion on X_S measurement has not been investigated systematically for the case where this effect is comparable to the intrinsic temperature dependence of X_S such as in superconductors, in a manner where the results are clearly available to others. In particular, this problem is very serious in the high temperature superconductors, where measurements for a wide temperature range is needed very often, or in the organic superconductors whose thermal expansion is very large. In this paper, we will quantitatively clarify the effect of thermal expansion of superconductors in the microwave measurement based on the systematic investigation of Z_S of Pb and Nb whose electromagnetic properties have been known very well with various sample sizes [7,8].

2. Experimental

We made microwave measurements on bulk samples of Pb and Nb with four different sizes. The dimensions of rectangular samples are $1.10 \times 1.02 \times 0.30$ mm^3 (Pb#L), $0.63 \times 0.63 \times 0.30$ mm^3 (Pb#S), $0.70 \times 0.70 \times 0.40$ mm^3 (Nb#L), and $0.48 \times 0.46 \times 0.18$ mm^3 (Nb#S), respectively. The microwave loss, $\Delta(1/2Q)$, and the frequency shift,

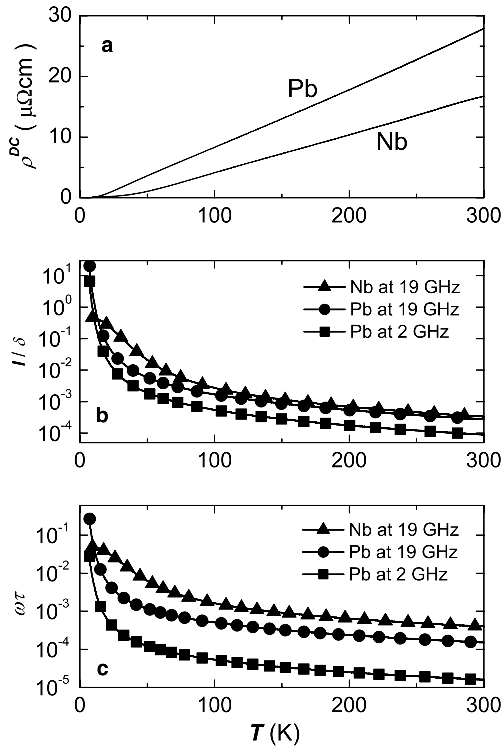

Fig. 1. The temperature dependence of (a) ρ_{DC}, (b) the estimated l/δ, and (c) the estimated $\omega\tau$, of Pb and Nb.