Temperature and Frequency Dependence of the Surface Resistance in the Vortex State of Type-II Superconductors

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The temperature and frequency dependence of surface-resistance data obtained in the vortex state of superconducting Pb-In alloys are analyzed. Measurements near H_{c2} indicate the normalized slope $s_2^{\perp}=(H_{c2}/R_n)\,\partial R/\partial H\,|_{H_{c2}}$ tends to go to zero as the critical temperature is approached. The data are accounted for qualitatively if the frequency dependence of the flux-flow conductivity (dynamical fluctuations) is retained in the expression for the microwave current. There is no exact quantitative agreement, and the possibility of a strong-coupling correction is suggested.

In a recent paper,[1] henceforth to be called I, we made a comparison between experimental surface-resistance measurements near H_{c2} in type-II superconductors and the microscopic flux-flow theory.[2] At low temperatures the agreement between theory and experiments was excellent, and the $\kappa_2(t)$ parameter deduced from the surface-resistance measurements agreed with magnetization data obtained from the same samples.[3] Near T_c, however, systematic deviations were observed and attributed to dynamical fluctuations of the vortex structure. These fluctuations are contained in our flux-flow expression for the conductivity $\sigma_s(H,\omega)$, and if we retain the frequency dependence of σ_s in the calculation of the surface resistance $R(H,\omega)$, we can account for the deviations observed. It is the purpose of the present note to examine this claim in some detail.

For the microwave current $\vec{j}_\omega$ we found in I [Eq. (11)]

$$\vec{j}_\omega=\left\{-i\omega\sigma-\frac{2e^2\tau N}{m}\left[\Psi\left(\frac{1}{2}+\frac{i\omega}{2\pi T}+\rho\right)-\Psi\left(\frac{1}{2}+\rho\right)\right]\frac{|\Delta(\vec{r},t)|^2}{2\epsilon_0(t)+i\omega}\right\}\vec{A}_\omega\ . \quad (1)$$

If we derive the conductivity $\sigma_s(H,\omega)$ as in I but keeping terms in $\omega/\epsilon_0(t)$, we find

$$\sigma_s(H,\omega)=\sigma-\frac{\langle M\rangle}{DH}\,\frac{1}{1+ix}\ , \quad (2)$$

where $x=\omega/2\epsilon_0(t)$. An expression for the surface impedance Z near H_{c2} can then be derived as in I, and from it we calculate the normalized slope $s_2^{\perp}(t,\omega)$, finding

$$s_2^{\perp}(t,\omega)=s_2^{\perp}(t,0)\,\frac{1+x(t)}{1+x^2(t)}\ . \quad (3)$$

$s_2^{\perp}(t,0)$ was found in I and for our samples reduces to

$$s_2^{\perp}(t,0)\cong 0.862[\kappa_2(0)/\kappa_2(t)]^2. \quad (4)$$

The factor $f(x)=(1+x)/(1+x^2)$ describes the extra absorption arising from the dynamical fluctuations and has its most pronounced effect near T_c. In that region

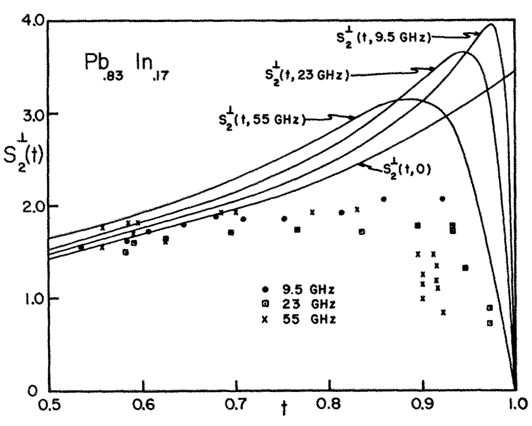

FIG. 1. Normalized slope $s_2^{\perp}(t)$ at H_{c2} of the surface resistance of a $Pb_{0.83}In_{0.17}$ alloy at frequencies of 9.5, 23, and 55 GHz. The curves are calculated as per Eqs. (3) and (4) of the text.

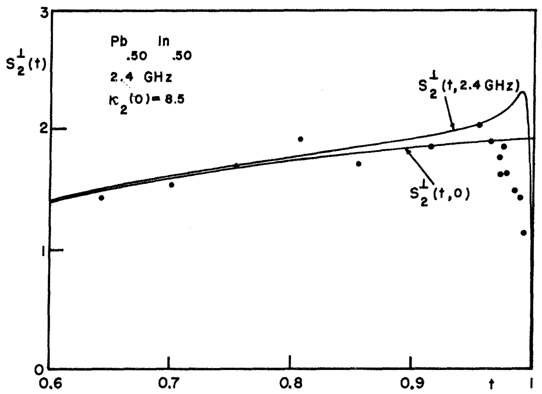

FIG. 2. Same as Fig. 1 for a $Pb_{0.50}In_{0.50}$ alloy at 2.4 GHz.

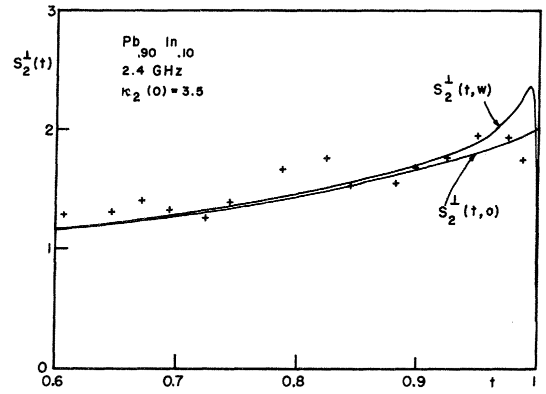

FIG. 3. Same as Fig. 1 for a $Pb_{0.90}In_{0.10}$ alloy at 2.4 GHz.

$$s_2^{\perp}(t,\omega)\Big|_{t\to 1} \to s_0^{\perp}(t,0)\,\frac{2\epsilon_0(t)}{\omega} \to 0 \;. \qquad (5)$$

At low temperatures, $s_2^{\perp}(t,\omega)\to s_2^{\perp}(t,0)$, which gives excellent agreement with experiments as reported in I.

Figures 1–3 show the calculated and measured slopes $s_2^{\perp}(t,\omega)$ for our samples.[4] The agreement is qualitatively good; but the measured data do not have the peak corresponding to the region $0<x<1$, where $f(x)>1$. In that region our theory predicts that the combined absorptions by flux-flow and fluctuations should be less than the absorption arising from flux-flow alone. This feature cannot be concluded from the experimental data. The increase in absorption [corresponding to a decrease of $s_2^{\perp}(t,\omega)$ in our figures] and its frequency dependence, however, are quite well reproduced when $x>1$. At present we do not know what prevents a better agreement between experiments and theory except to suggest that this may be a strong coupling effect, such that $x=\omega/2\epsilon_0(t)$ may have to be replaced by $x^*=\omega/2\epsilon_0^*(t)$, the asterisk indicating a renormalized quantity. With a ratio $\epsilon_0^*/\epsilon_0=2.2$ the agreement between measured and calculated $s_2^{\perp}(t)$ is very noticeably improved. This can be seen in Fig. 1 by comparing the experimental data at 23 GHz with the calculated curves at 23 and 55 GHz.

In conclusion, we have seen that the microscopic theory of flux-flow explains the observed surface resistance very well at low temperature and that the dynamical fluctuations give a qualitative fit to the observed behavior near T_c.

[1]G. Fischer, R. D. Mc Connell, P. Monceau, and K. Maki, Phys. Rev. B 1, 2134 (1970).

[2]This theory is given in Ref. 1, together with full references to earlier work on flux-flow theory.

[3]J. le G. Gilchrist and P. Monceau, J. Phys. C 3, 1399 (1970).

[4]The experimental data presented in this paper are the same as in I. We should like to acknowledge again that the 23- and 55-GHz data have been supplied by Dr. B. Rosenblum, Dr. J. I. Gittleman, and Dr. A. Rothwarf of the RCA Laboratories, Princeton, N. J.