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High-Frequency Resistance of Tin and Indium in the Normal and Superconducting State

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Additional measurements have been made on the surface resistance of tin and indium near 24 000 Mc/sec. The results are in general agreement with those reported previously. The high-frequency resistance appears to be varying with frequency in the superconducting region as the three-halves power rather than the predicted second power. This appears to be the case for both tin and indium.

The effect of evaporating a thin indium film over an electroplated film is discussed. Data for the normal state are in general agreement with the Reuter-Sondheimer theory of the anomalous skin effect.

ADDITIONAL measurements have been made on the surface resistance of tin and indium at frequencies near 24 000 Mc/sec. The results are in general agreement with those reported previously.[1] The method used is the same as that described in the earlier paper. The electric Q factor is measured as a function of temperature and the surface resistance calculated from the measurements.

TIN

The results in the normal state are in agreement with the earlier work. In the superconducting state the results are slightly different from the preliminary measurements reported previously.[1] The residual resistance at absolute zero is 0.2 percent of the resistance at the transition. The more recent measurements[2] are more precise than the earlier measurements. A higher-mode cavity was used which made it possible to measure the Q values more precisely. Table I gives the values of the normal conductivity, the residual resistance at absolute zero, and the values of $A(\omega)$. $A(\omega)$ is the slope of the linear plot of R/R_n *versus* $f(t)\equiv t^4(1-t^2)/(1-t^4)^2$, where R_n is the surface resistance in the normal state just above the transition temperature T_c, and t is the reduced temperature T/T_c. The value of $A(\omega)$ for tin at 24 000 Mc/sec is 0.24. This compares with our preliminary value of 0.265. Fawcett,[3] in some recent work on tin, has also determined $A(\omega)$ at 24 000 Mc/sec and obtained a value of 0.24. He used an electrolytic polished surface. If Pippard's results at 1200 Mc/sec are extrapolated to this higher frequency using the assumption that in the superconducting region the resistance is varying with frequency as the three-halves power, the value of $A(\omega)$ obtained is 0.238. The measured values appear near this extrapolated value. The results would also indicate there is little difference between an electropolished surface and a mechanically polished surface. Figure 1 is a linear plot of the low-temperature resistance *versus* $f(t)$; the slope $A(\omega)$ is determined from this figure. Figure 2 is a plot of the normalized surface resistance *vs* temperature. The curve is very similar to the one at the lower frequency except that at temperatures near 3.4°K the curve is more rounded than the curve for the lower frequency.

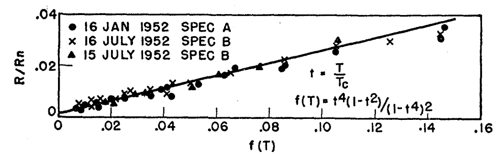

FIG. 1. Linear plot of low-temperature resistance of tin.

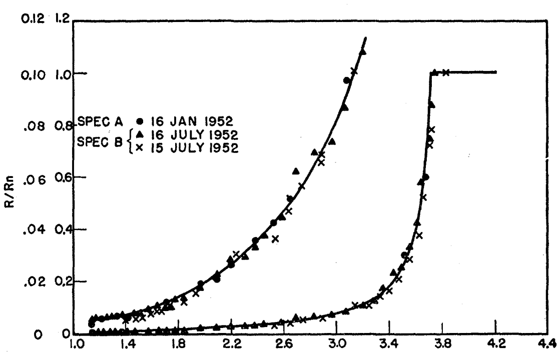

FIG. 2. Surface resistance of tin in superconducting state. The ordinate scale 0–1.2 applies to the lower curve. The upper curve represents the same data on an ordinate scale expanded 10×.

INDIUM

Indium acts very similarly to tin in its behavior in the superconducting region. The curve of the normal-

TABLE I. Experimental results.

Frequency Mc/sec	Metal	Normal surface conductivity ohm⁻¹	R/R_n extrapolated to absolute zero	$A(\omega)$	Remarks
9145	Tin	150	0	0.127	Polished, electroplate
9137	Indium	40	0.005	0.081	Electroplated
24 185	Indium	34	...	...	Polished, machined
24 050	Indium	31	0.007	0.21	Electroplated
24 080	Tin	79	0.002	0.24	Polished, machined

[1] C. J. Grebenkemper and J. P. Hagen, Phys. Rev. **86**, 673 (1952).
[2] A portion of this paper was presented at the Schenectady Cryogenics Conference, 1952. [*Note:* An error exists in the printed abstract of the meeting. $A(\omega)$ should be 0.24 rather than 0.25.]
[3] E. Fawcett (private communication).

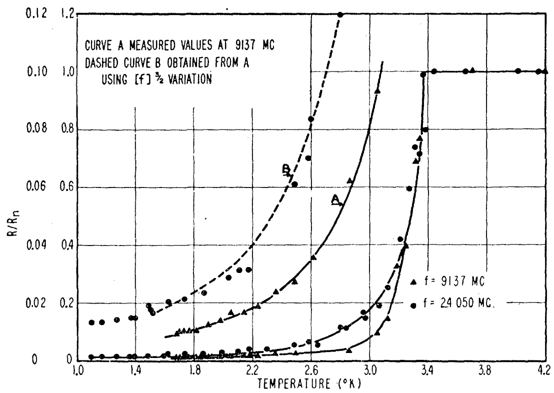

FIG. 3. Surface resistance of indium. The ordinate scale 0–1.0 applies to the lower curves. The upper curves represent the same data on an ordinate scale expanded 10×.

ized surface resistance *vs* temperature is shown in Fig. 3. If the "superconducting resistance" is assumed to vary with frequency as the three-halves power of frequency and the results obtained at the lower frequency are extrapolated to this frequency the dashed curve is obtained. It can be seen in this figure that the measured experimental points lie rather close to the extrapolated curve.

The indium was deposited on a brass base designed to fit a cavity holder. The electroplated surfaces were plated from the Indium Corporation of America patented bath Cy-An-In. No further treatment after plating was given the finished product. The appearance of the film was very good, being much superior to that surface used in the previous work.[1] After measurements were completed on one specimen, a thin film of indium was evaporated in a bell jar under a reasonably high vacuum and the conductivity measurements repeated. The results are shown in Fig. 4. It can be seen from this figure that the evaporated film has a lower value of conductivity than the electroplated film. The normal conductivity changed very little which was as expected. In the superconducting region the conductivity was lower. The lower value of conductivity could be ascribed to the material coming off in an amorphous mass and numerous faults existing in the surface. Scattering may be taking place at these faults thus giving rise to an abnormally high resistance.

Measurements were made on an indium surface that was mechanically polished. The indium was cast in a brass holder and the inner surface machined and polished in a similar manner to that of tin. The polishing process was rather difficult since indium is extremely soft. After the specimen was polished an attempt was made to clean the surface by using a dilute solution of HCl. The experimental results are shown in Figs. 3 and 4. The polished indium specimen did not yield as high a value of conductivity as the electroplated specimen in the superconducting region. This could be caused by the polishing techniques or to some etching taking place in the attempt to clean the specimen after polishing.

The values of the normal conductivity are given in Table I. The value at 9100 Mc/sec is lower than would be expected if indium behaved in a similar manner to tin. The values obtained at 24 000 Mc/sec are almost as large as the values at 9100 Mc/sec. This may be caused by the poor surface used at 9100 Mc/sec and the much better surface used at 24 000 Mc/sec.

CONCLUSIONS

It appears that the resistance in the superconducting region is varying with frequency as the three-halves power of the frequency rather than the predicted

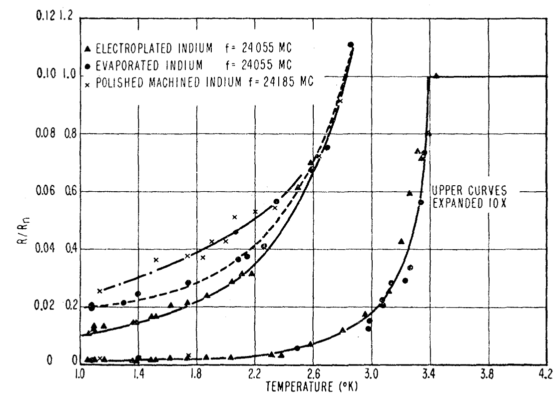

FIG. 4. Surface resistance of indium. The ordinate scale 0–1.0 applies to the lower curve. The upper curves represent the same data on an ordinate scale expanded 10×.

variation of the second power. This relationship appears to apply for both tin and indium. For tin the residual resistance at absolute zero is 0.2 percent of the resistance at the transition temperature. The value of $A(\omega)$ for tin is 0.24. For a good polished surface it is quite possible that the residual resistance would approach zero at absolute zero. For an electroplated indium surface the residual resistance is 0.7 percent and $A(\omega)=0.21$. These results are for an untouched electroplated film. For a good polished indium surface the indium results would probably be very similar to tin.

ACKNOWLEDGMENT

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