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Indications of a High Mobility Surface Layer on Oxidized Copper and Aluminum Surfaces at Low Temperatures

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We discuss progress in the comparison of the temperature dependence of the microwave surface impedance and of the spatial variations in the surface potential on oxidized copper and aluminum. These measurements test the hypothesis that sharp increases in the microwave surface conductivity of copper and aluminum are caused by the appearance of a high mobility surface layer at low temperatures. An in-situ evaporator in our UHV surface potential apparatus will allow work function measurements of well-characterized surfaces, but the samples must be transferred in air to the surface impedance experiment.

1. INTRODUCTION

In the models suggested by Bardeen[1] and Hanni and Mady[2] to explain the absence of large electric "patch effect" fields[3,4,5] above copper, a polycrystalline metal surface, a layer of electrons bound to the surface oxide layer of a metal becomes conducting at low temperatures. Calculations show[2] that electron densities on the order of \(10^{12}\) electrons/cm\(^2\) will substantially screen potential variations on the metal surface.

We have constructed two experiments to investigate this effect more directly. The first of these is a system for high precision measurements of the microwave surface impedance of metals at low temperatures. With this apparatus we have found sharp, anomalous increases in the surface conductivity of copper and aluminum surfaces as the temperature is decreased. Such anomalies would be generated by an increase in the number of conducting surface electrons. The second experiment is a surface potential probe which can measure directly the local electric fields above a metal surface as a function of position. We report here on modifications of the microwave cavity apparatus to accept samples compatible with the surface potential apparatus.

Examining the same samples in both experiments indicates whether the surface impedance anomalies are in fact caused by an additional surface conducting layer capable of screening surface potential variations.

2. EXPERIMENTAL DETAILS

The microwave cavity system can measure the resonant frequency of a cavity as a function of temperature to better than 1 part in \(10^{15}\) at its resonant frequency of 9 GHz over the temperature range 2-20 K. For cavities made of pure metals at low temperatures (i.e., in the "extreme anomalous limit" of the surface impedance) one finds that the shift depends only upon the surface carrier density \(n\), the effective mass \(m\), and the scattering time \(\tau\).

\[ \Delta f (\text{Hz}) = 10^{12} \left( \frac{m}{m_0} \right) n (\text{cm}^2/\text{eV}) \times \begin{cases} \omega \tau & \text{if } \omega \tau \ll 1 \\ 1 & \text{if } \omega \tau \gg 1 \end{cases} \]

In general, changes in the conductivity of the surface layer of \(10^{12} - 10^{14}\) electrons/cm\(^2\) can be detected.

We have observed sharp changes in the resonant frequency as a function of temperature in cylindrical cavities made of copper and aluminum. The effective surface conductivity increases as the temperature is lowered. The anomalies were stable and reproducible from run to run; the effect on one sample was unchanged after an interval of over a year.

Figure 1 shows the frequency shift as a function of temperature for several magnetic fields applied along the axis of the cavity. The effect of the field is strongly temperature dependent, with the suppression largest at higher temperatures. A field of 200 gauss suppresses the anomaly almost entirely, bringing the \(f(T)\) curve very near to the extrapolation of the fit to the thermal expansion form above the anomaly.

![Graph](image_url)

Fig. 1. Resonant frequency of the microwave cavity as a function of temperature in different axial magnetic fields. The thermal expansion background has been fit and subtracted.

Since the appearance of a surface conducting layer would reduce the spatial variation of the surface potential as discussed earlier, we have developed a work function apparatus operating in UHV and at cryogenic temperatures. A rotating electrode forms a capacitor with the sample, which
is mounted below it on an adjustable stage. The changing voltage across this capacitor by the electrode moves to a region of different sample surface potential causes charge flow to and from the sample. This signal is converted to a voltage by the low temperature amplifier and signal averaged. The result is a measurement of the surface potential along an annulus (see fig. 2). Cryogenic temperatures are obtained by immersing the probe in liquid helium.

Fig. 2. The 77 K surface potential along an annulus of polycrystalline copper annealed at 1000 C for six hours, resulting in macroscopic crystallites. Sample temperatures of 2.9 K are attained in the surface potential apparatus.

We presently operate with a spatial sensitivity of one millimeter and a voltage sensitivity of one millivolt. Two polycrystalline copper samples, one annealed to grow crystallites large enough to generate resolvable potential changes above the surface, have been measured at temperatures down to 2.9 K. Neither showed evidence of a shielding effect at the present limit of sensitivity. In the microwave cavity experiment, however, we know that the low temperature anomaly did not appear on all samples at the original level of sensitivity, or at all on some.

3. DISCUSSION

We have ruled out a number of explanations for the anomalies. However, the possibility of a superconducting contaminant cannot be completely eliminated at this time. We have deliberately introduced a superconducting contaminant, and observed frequency shifts and magnetic effects similar to those described above. But the amount of contaminant must be quite large - about $10^{-2}$ cm$^{-2}$ for a 50 Hz. shift. Furthermore, we observe a small but clear perturbation to the anomaly with deliberate surface contamination (helium, oxygen, hydrocarbons), which suggest a surface phenomenon. With the modified experiment described below, we can control and analyze the sample purity sufficiently to determine whether a superconducting contaminant is responsible for the conductivity anomalies.

4. FURTHER WORK

We have modified the surface impedance experiment to accept, as a removable insert in the cavity wall, a sample compatible with our surface potential apparatus. The insert and cavity are thermally isolated from one another so that their temperatures can be varied independently. Surface potential measurements of a sample with a surface impedance anomaly would clearly test the existence of a shielding conducting layer of electrons. Preliminary measurements of one insert show no anomalous effect, although the main cavity has a small but clearly recognizable temperature dependent frequency shift (see Fig. 3).

Figure 3 shows the frequency shift on application of a 200 gauss magnetic field. As can be seen in Fig. 1, there is a temperature dependent shift in the resonant frequency with axial magnetic field only below the transition temperature. (In Fig. 3, a shift with magnetic field due to the constant 2.5 K temperature of the main cavity has been subtracted, as well as a temperature independent shift of the insert with magnetic field). The method of Fig. 3 eliminates long term drift, resulting in a more sensitive measurement.

Fig. 3. Shift in resonant frequency of the microwave cavity on application of a 200 gauss magnetic field. The triangles are shifts in the main cavity; the pluses are for the thermally isolated insert (see text).

We are currently installing a resistive evaporator in the surface potential apparatus so that surfaces can be deposited in-situ at low temperature. However, samples must be transferred in air to the surface impedance probe.

REFERENCES