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KONDO RESISTIVITY IN COPPER-CHROMIUM AT 35 GHZ

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Abstract.- The microwave surface impedance at 35 GHz has been measured at temperatures down to 80 mK for chromium concentrations between 30 and 150 ppm. The temperature, at which the "Kondo" divergence in the resistivity saturates as the alloy is cooled, is shown to be strongly enhanced at these frequencies over its value for static resistivity.

Conduction electron scattering by a magnetic impurity in a normal metal is expected to be strongly peaked near the Fermi level at very low temperatures. As a result the bulk resistivity of a dilute magnetic alloy should be a function of the frequency of the applied fields. This frequency dependence is in addition to that of the ordinary Drude resistivity seen in normal metals, which is of the order of a 10% effect at 35 GHz in our most dilute alloy. Present models predict a qualitative effect to be expected in dilute alloys as the frequency is increased from d.c. towards \( \omega_c \), where \( \omega_c = k_B T_K \) (\( T_K \) is the Kondo temperature). At high temperatures, the d.c. and microwave resistivities should be similar, varying with temperature with the characteristic negative slope on a log T plot. As \( T \) approaches approximately \( \omega_c / k_B \), the microwave resistivity should cease to increase with decreasing temperature, and remain constant down to \( T = 0 \). For \( \omega = 35 \text{ GHz} \), this temperature is about 530 mK.

Previous measurements in the Cu (Cr) system \(^{2,3} \) at \( \omega = 10 \) and 70 GHz, extending down to about the saturation temperatures at these frequencies did not show the saturation effect, but indicated that at 70 GHz, the slope of the resistivity increased above its d.c. value, and did not appear to scale with concentration at the concentrations used. At 10 GHz on the other hand, the slope was below its d.c. value, and scaled with concentration.

The present work extends these measurements to 35 GHz. We measure the microwave heating in our sample. The sample and references form ends of a 35 GHz, TE\(_{031}\) mode cylindrical cavity having lead plated stainless steel side walls, brazed to a central copper plane and bolted to a dilution refrigerator. The electropolished samples were prepared as in our earlier work at 10 GHz, using the same master alloy.

Our data take us well into the anomalous skin effect regime. To facilitate comparison with the static resistivity, we have used the the anomalous skin effect formula of reference \(^4\) to calculate an effective resistivity \( R(35 \text{ GHz}) \) from our surface impedance results (Fig. 1). This formula ignores the Drude term and the frequency dependence of transport relaxation time, both of which may be significant at 35 GHz, but no treatment which includes both these effects is available.

From figure 1, three pieces of information can be obtained for each of the three samples run: the high temperature slope, the saturation resistivity at low temperature, and the "corner" temperature \( T^\text{exp} \), at which the resistivity bends over. These values, together with two other "corner" temperatures are given in table I. In the static resistivity results, impurity-impurity interactions cause the resistivity to bend over at a concentration dependent temperature \(^5\), \( T^\text{d.c.} \) (the curve in figure 1 is an example).
Effective resistivity of three copper-chromium alloys at 35 GHz., versus temperature. The curve shows the d.c. resistivity of a 30 ppm alloy.

Table I

<table>
<thead>
<tr>
<th>c (ppm)</th>
<th>R(T=0)/c (nΩ.cm/ppm)</th>
<th>slope</th>
<th>θ (°)</th>
<th>θ (°)</th>
<th>θ (°)</th>
<th>d.c. (K)</th>
<th>exp. th. (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1.70</td>
<td>0.875</td>
<td>0.360</td>
<td>0.359</td>
<td>0.133</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>2.00</td>
<td>0.632</td>
<td>0.365</td>
<td>0.269</td>
<td>0.187</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>1.73</td>
<td>0.382</td>
<td>0.370</td>
<td>0.251</td>
<td>0.508</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The slope of d.c. resistivity of a 30 ppm alloy is -0.508 nΩ.cm/ppm/decade, and decreases with increasing concentration, so that the slope of the resistivity at 35 GHz is greater than that at d.c. in all three alloys.

Concentration dependent effects enter into a discussion of these results in two very different ways. First, we know from static measurements that impurity-impurity interactions are important in these alloys, at least at 70 and 150 ppm, as is indicated by the large increase in $\theta_{d.c.}$ with concentration. In addition, even in the absence of interactions, the relative importance of the Drude term varies inversely with concentration, and prevents the resistivity from scaling with concentration at high frequencies and low concentrations, even for nominally isolated impurities. This latter effect is evidenced by the variation of the "corner" temperature $\theta_{th.}$ in table I. To obtain $\theta_{th.}$ we redid the calculation of ref. /1/, finding $R(35\text{ GHz})/c$ from the s-d model with $T_K = 2.2\text{ K}$, impurity spin $= \frac{1}{2}$, and no potential scattering. The results were qualitatively similar to figure 1, except that both $R(T = 0)/c$ and the slopes decreased in magnitude with increasing frequency and decreasing concentration. However, we did not include the anomalous skin effect in our calculation, so these remarks are (at best) only suggestive.

Thus the primary effect of going to 35 GHz is that the expected increase of the corner temperature over its d.c. value is in fact seen for the first time in an alloy, sufficiently dilute that interaction effects are unimportant. An additional (and unexplained) result is that the corner temperature in more concentrated alloys is less than that produced in the same alloy at zero frequency by impurity-impurity interactions.

References