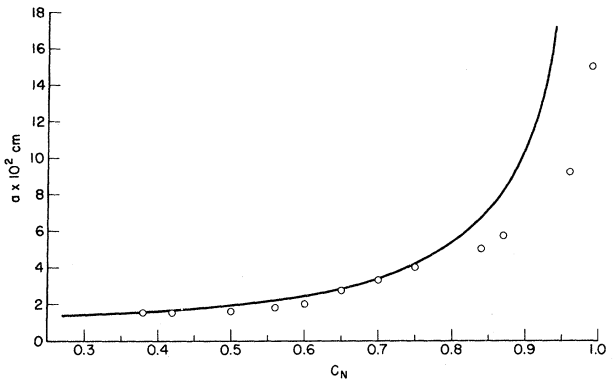

FIG. 3. The spatial periodicity of the domain structure, a, as a function of C_N for a tin sample 0.75 mm thick, $\beta = 16.8°$, and $T = 2.0$ K. The points are experimental results, while the line is calculated from the Landau model.

quired for the passage of a single domain between the two points, together with the time interval for two adjacent domains to pass one of the points, then allowed the spatial periodicity of the moving structure to be established. Proceeding as in Ref. 4, this periodicity can then be compared with the predictions of the Landau model. The only quantity which enters the calculation and is not obtained directly during the experiment is the surface tension parameter and, as in Ref. 4, the value obtained in Sharvin's work[3] was adopted. The result of the calculation is compared with experiment for $T = 2.0$ K in Fig. 3. Over most of the range it is clear that the moving structure has a periodicity very close to that predicted by the Landau model. The departures at high fields have already been discussed in Ref. 4 in terms of a changeover to a modified Landau structure.

It is concluded that a new experimental regime has been discovered in which domain motion can be realized under ideal conditions. All features of such motion can now be studied with much more precision than hitherto. The method is being actively applied to other type-I materials as well as to a comprehensive study of tin itself.

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One-Dimensional Superconductors

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We report here measurements of the excess fluctuation conductivity in one-dimensional Al samples. Because sample diameters were so small (typically, square cross sections ~600 Å×600 Å), we were able to measure excess conductivity over a temperature range much wider than previously possible. Good agreement with the Thompson-Maki theory is observed at temperatures $T < 1.3T_c$. The recent theory due to Patton is also in qualitative agreement. Above $1.4T_c$ the data do not agree quantitatively with any theory.

Fluctuation effects in the superconducting resistive transition of one- and two-dimensional samples have recently been observed and reported.[1,2] A one-dimensional sample is a wire in which the Ginzburg-Landau (temperature-dependent) coherence length $\xi(T)$ is much larger than the x or y dimension (z being the wire axis), while a two-dimensional sample is a film of thickness t with $\xi(T) \gg t$, and all dimensions in the film plane being $\gg \xi(T)$. Although the region below T_c has been extensively explored for one-dimensional samples and is on reasonably sound ground theoretically[3,4] and experimentally,[1] the region above T_c is less well understood. In particular, there are relatively few data available in this region taken on one-dimensional samples. The problem is that while the coherence length is infinite at T_c, it drops rapidly as temperature increases.[5] Thus samples which are one-dimensional near T_c cease to be one dimensional at higher temperatures. For wires, the temperature range over which the sample is one-dimensional increases

as wire diameter decreases. Data on fluctuation conductivity over a large temperature range are desirable in order to test proposed theoretical models, and this in turn requires that wires of very small diameter be available for which the requirements of one-dimensionality are satisfied over a large temperature range above T_c.

In this Letter we report measurements of excess conductivity in one-dimensional Al samples which are, in fact, the finest "wires" ever fabricated. Samples were fabricated by applying an electron-beam lithography technique, described elsewhere,[6] to evaporated thin films. High-purity Al sources (total impurity content $\lesssim$ a few ppm) were used. Typically, samples were well-defined stripes, 140 μm long with wide pads at each end for making contact (see insert in Fig. 1). Sample cross sections were approximately square and constant in area (and shape) along the length of the stripe. The smallest wire prepared by this method had a 500 Å $\times$ 600 Å cross section. Scanning electron microscopy was necessary to determine these dimensions and to insure that the samples had a high degree of uniformity. Because of the small cross-sectional area, the normal-state resistance of these stripes was high (typically >1000 Ω at 4.2°K), and the fluctuation conductivity was very large. This allowed us to observe resistive fluctuation effects at temperatures close to $2T_c$ with fairly conventional circuitry; e.g., nanovolt sensitivity and a current density J of 10^3 A/cm^2 were used. The resistive characteristics did not depend on current density if $J \leq 2 \times 10^3$ A/cm^2.

The excess conductivity results (σ') on a Al "wire" 600 Å wide and 700 Å thick are shown by the dots in Fig. 1. The sample was relatively "clean" in that its resistivity decreased by a factor of 1.93 as it was cooled from room temperature to just above the superconducting transition. The electron mean free path l at this temperature was determined to be 203 Å from the measured resistivity ρ and the published value[7] $\rho l = 8.2 \times 10^{-6}$ $\mu\Omega$ cm^2. These numbers are typical of the several wires tested. In order to compare the temperature dependence of the excess conductivity with theory, we have included in Fig. 1 the results from three theoretical treatments which have been fitted to the experimental parameters. The smooth curves in Fig. 1 are due to Aslamov and Larkin[8] (A-L), Thompson-Maki[9] (T-M), and Patton[10] (P). It can be seen that the measured excess conductivity is substantially larger than that predicted by the A-L theory, $\sigma_{A\text{-}L}'$. However, the temperature dependence of the data is in approximate agreement with the A-L theory, i.e.,

$$\sigma_{A\text{-}L}' = \frac{\pi e^2 \xi(0)}{16\hbar S}\left(\frac{T-T_c}{T_c}\right)^{-3/2} \equiv \tau_0 \tau^{-3/2}, \qquad (1)$$

over the range $(1.1\text{–}1.4)T_c$; in Eq. (1), S is the cross-sectional area of the sample. The temperature dependence is more clearly seen in Fig. 2 where the data are plotted as a function of τ. Above $1.3T_c$ the measured σ' falls off more rapid-

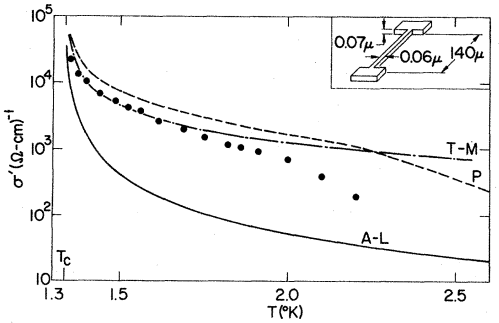

FIG. 1. Plot of the excess conductivity σ' versus temperature (heavy dots) for the Al sample shown in the insert, compared with existing theories. For this sample, $T_c = 1.336$°K, mean free path $l = 203$ Å, and normal state resistivity $\rho = 4.03$ $\mu\Omega$ cm.

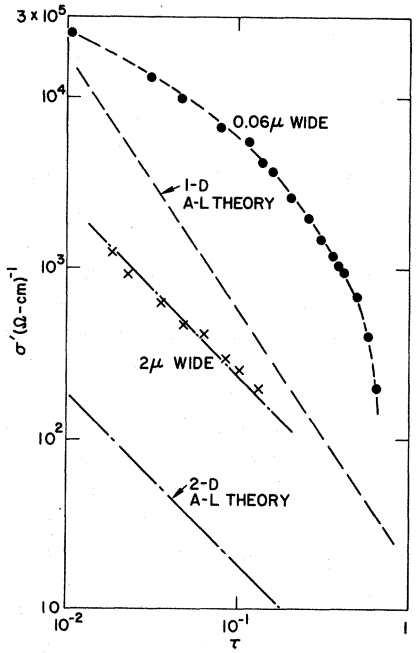

FIG. 2. Plot of σ' vs $\tau[=(T-T_c)/T_c]$ for two Al samples, which are identical in all respects except for their widths. Data points for the two-dimensional sample cover a smaller temperature range because the excess conductivity is intrinsically smaller than for the one-dimensional sample and was therefore not resolvable over as wide a temperature range.

ly and again approaches $\sigma_{A\text{-}L}'$. A better fit to the data is obtained with the T-M modification of the A-L theory. This modification postulates that in real samples there exist pair-breaking mechanisms which are required to give a nondivergent fluctuation conductivity, and predicts an excess conductivity

$$\sigma_{T\text{-}M}' = \sigma_{A\text{-}L}'\left[1 + \frac{4\tau/\tau_c}{1+(\tau/\tau_c)^{1/2}}\right]. \quad (2)$$

In this equation the adjustable parameter τ_c is defined as $(T_c - T_c^*)/T_c^*$, where T_c^* is the transition temperature which the sample would have in the absence of pair-breaking mechanisms. The T-M curve in Fig. 1 is plotted using a τ_c of 0.01, and a reasonable fit to the data is achieved up to about 1.8°K (i.e., $\sim 1.3T_c$). Beyond 1.8°K the data deviate from the T-M theory as expected. Thompson estimates that the validity of his theory is questionable once $\sigma'/\sigma_n \ll \tau_c$ which is the case for $T > 1.8$°K (σ_n being the normal state conductivity). Patton's theory, in which the finite lifetime of the interacting electrons is included, gives the result

$$\sigma_P' = \sigma_n\left(\frac{\eta_0}{\eta}\right)^{3/2}\left[4\sqrt{2} - 3 - \frac{2\sqrt{2}}{\pi}\frac{\eta^{5/4}}{\eta_0^{3/4}}\ln\left(\frac{\pi}{4\eta}\right)\right], \quad (3)$$

where $\eta_0^{3/2} = \tau_0/\sigma_n$ and $\eta = \ln(T/T_c)$ for temperatures above T_c. It can be seen in Fig. 1 that Patton's theory which does not contain any adjustable parameters provides fair qualitative agreement with the experimental data. In particular, only Patton's theory predicts a high-temperature inflection point in the temperature dependence of σ' as is actually observed in the data.

A two-dimensional sample was deposited in the same evaporation and on the same substrate as the one-dimensional sample of Fig. 1. The two samples were identical in every respect except width. The excess conductivity for this sample (shown in Fig. 2) was about an order of magnitude larger than the A-L prediction for two-dimensional samples but followed the predicted temperature dependence ($\tau^{-1/2}$). These results for the two-dimensional samples are therefore in good agreement with those previously obtained.[2,11]

In conclusion, we have measured the excess fluctuation conductivity above T_c in one- and two-dimensional Al samples. Our results for two-dimensional samples are in good agreement with previously reported measurements. For the one-dimensional case, our sample fabrication methods have allowed us to cover a much larger temperature range than was previously possible (up to about $2T_c$). Past measurements[12,13] were reported on samples which are one dimensional only for temperatures below about $1.2T_c$. In this temperature range we find general agreement with the previous work and with the Thompson-Maki and Patton theories. At higher temperatures, the data cannot be fitted with any of the existing theories.

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