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# Intermediate State of Hard Superconductors

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The very large domains found in the intermediate state of hard superconductors are investigated. It is found that pure, annealed rhenium shows fine domains like other soft superconductors, but that coarse domains can be produced by cold-working the sample. Thus the large domains are not due to peculiar electronic properties of the hard superconductors, but to locally strained or impure boundary regions.

## I. INTRODUCTION

THE hard superconducting metals are distinguished from the soft superconductors by their larger ratio of critical magnetic field to transition temperature. Characteristically, they also show more magnetic hysteresis and flux trapping. As the metals are prepared in purer and less strained form, these differences decrease, but it is seldom possible to remove them entirely.

One of the most striking differences in behavior is observed in the intermediate state.[1] When a magnetic field of suitable magnitude is applied perpendicular to the face of a superconducting plate, superconductivity is destroyed in some regions, while a portion of the plate remains normal. In a soft superconductor, such as tin or aluminum, these superconducting domains are small and closely spaced. From their average spacing one can infer a value of the interphase boundary energy.[1,2] With hard superconductors, such as vanadium, tantalum or niobium, the domain size is very much larger,[2] although it also depends on sample thickness. If one were to infer a value of boundary energy from their domain spacings, it would be too large to explain by any of the present theories.

On the other hand, the large domain patterns in the hard superconductors might not be fundamental in origin, but might come from the strains and impurities which were present in even the best available samples. Some, although not all, features of the pattern seemed to persist on successive applications of the magnetic field to the sample. Bismuth probe measurements of the local magnetic field on the surface of a vanadium plate were made. They showed that motion of the domains was accompanied by large jumps of the magnetic field, but its value was in general neither zero nor the bulk critical field. It seemed, therefore, that the behavior of the hard superconductors might be due to locally strained or impure regions which act as barriers to field penetration. Once such a barrier is overcome, the field moves a long distance further into the sample until another one is reached. If all the strains and impurities could be removed, the sample would behave like a soft superconductor. However, none of the available samples showed anything but very large intermediate-state domains.

Alers[3] has observed similarly large intermediate-state domains in impure lead (containing $3\frac{1}{2}\%$ antimony). He was not able to resolve the domain structure in pure lead. We have observed that pure lead has an intermediate state like tin, but with an even smaller boundary energy. Thus the addition of impurities to lead can change its intermediate-state characteristics from soft to hard. However, it is not clear whether the change is caused by the simple introduction of inhomogeneous regions, or by a donor action of the antimony which changes the electronic structure of the lead.

## II. EXPERIMENTS WITH RHENIUM

It has been found[4] that rhenium of sufficient purity, which has been arc melted, behaves magnetically as a soft superconductor. However, cold-working transforms it into a hard superconductor. Vacuum annealing restores the soft behavior. It is therefore interesting to see whether this change is also reflected in the structure of the intermediate state.

Figure 1 shows the pattern observed when an annealed disk (diameter 1.37 cm, thickness 0.18 cm) of pure rhenium at 1.10°K is subjected to a magnetic field of 75 oersteds. At this temperature $H_c \approx 113$ oersteds so that $H/H_c = 0.66$. The pattern is very much like those found by Faber[2] in aluminum. That is, the domains are fine and although their walls are quite irregular their spacing is fairly uniform across the plate. The average spacing of about 0.29 mm can be used to calculate a rough value of the interphase boundary energy parameter, $\Delta$.[1,2] We have to pretend that the domains are infinite laminae, to apply the theory of Lifshitz and Sharvin[1,5] connecting the spacing with boundary energy. Then $\Delta = 7.3\times10^{-5}$ cm for $T/T_c = 0.647$. Faber[3] has proposed a correction dependent on $(\Delta/L)$, where $L$ is the plate thickness, to take into account a fluted domain wall. In this case the correction factor is 0.76, so that $\Delta = 5.6\times10^{-5}$ cm.

[1] A. L. Schawlow, Phys. Rev. **101**, 573 (1956).
[2] T. E. Faber, Proc. Roy. Soc. (London) **A248**, 460 (1958).
[3] P. Alers, Phys. Rev. **105**, 104 (1957).
[4] J. K. Hulm and B. B. Goodman, Phys. Rev. **106**, 659 (1957).
[5] E. M. Lifshitz and Yu. V. Sharvin, Doklady Akad. Nauk S.S.S.R. **79**, 783 (1951).

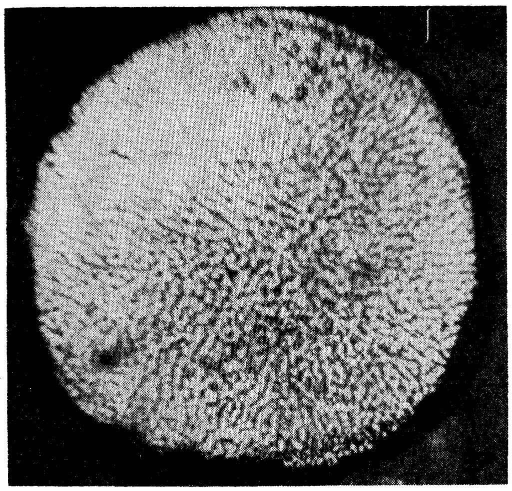


FIG. 1. Intermediate-state pattern of an annealed rhenium plate at 1.10°K, $H=75$ oersteds. The fine domains are characteristic of a soft superconductor.

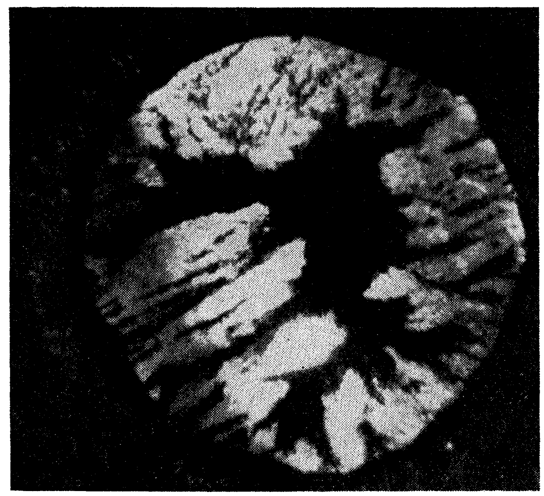


FIG. 2. Intermediate-state pattern of the same plate after surface grinding. The domains are now large, as in hard superconductors. Same temperature and magnetic field.

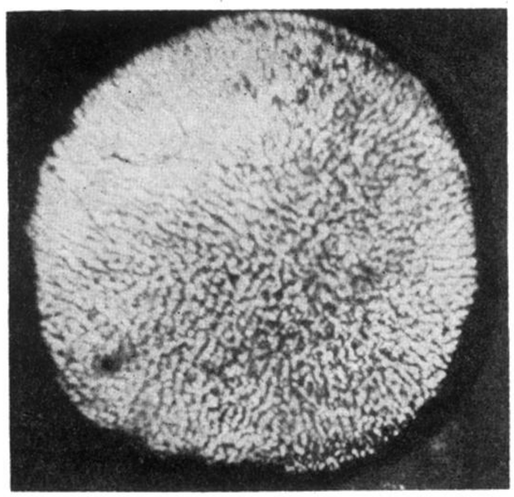
In either case the value of $\Delta$ is approximate, but it seems quite reasonable. It lies between the values for aluminum and for tin.

If the sample is cold-worked by grinding off about 0.12 mm from each of the flat surfaces, the pattern changes completely and the behavior is entirely that of a hard superconductor. Figure 2 shows the domain pattern for the cold-worked rhenium sample. The domains are much larger, even though the plate is thinner, and their spacing is quite irregular. When the applied magnetic field is changed, domain wall motion proceeds with abrupt jumps over large regions.

In the case of rhenium, cold-working alone without chemical contamination is sufficient to create the large domains characteristic of the intermediate state in hard superconductors. The hardening process seems to involve creation of filaments (probably thin) which act as barriers to flux penetration. It is clear that the intermediate-state behavior of the hard superconductors is not related in any fundamental way to their electronic structure.

### III. CONCLUSIONS

Because the large domains characteristic of hard superconductors can be produced in lead by impurities, or in rhenium by cold-working, and because the field inside them is not the critical field, it is concluded that they are not a fundamental property of those metals. It is much less likely for soft superconductors to be greatly affected by structural imperfections, because they anneal readily. One could be more certain of this, if the magnetic field on the surface of these domains could be measured with sufficient precision and spatial resolution. Meanwhile, the approximate regularity and quantitative agreement between different experimenters attest the fundamental nature of the domains in soft superconductors.



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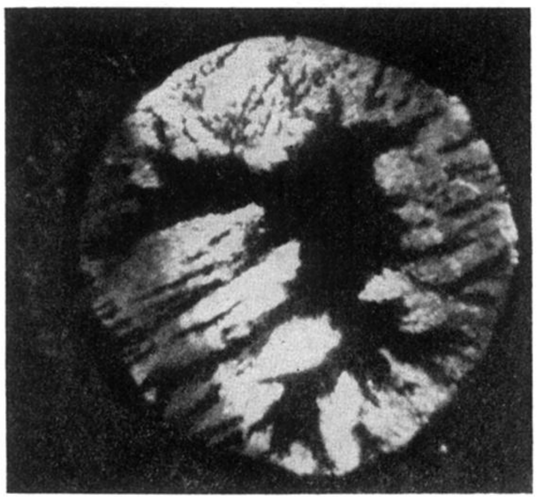

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