

# The electrical conductivity of thin metallic films

## III. Alkali films with the properties of the normal metal

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### 1. INTRODUCTION

In the present work the measurements of the resistivity of evaporated films of the alkali metals (Lovell 1936 *a*, *b*; Appleyard and Lovell 1937) have been extended to a thickness of several thousand angstroms. The previous results were limited to films of less than a few hundred angstroms in thickness; and it appeared that the increased resistivity of these thin films compared with that of the bulk metal was due merely to the shortening of the mean free path of the conduction electrons by collision with the boundaries of the film. It was therefore to be expected that at thicknesses much in excess of the mean free path the resistivity of the film material should closely approximate to that of the bulk metal.

The present results confirm this expectation only in the case of caesium, where the resistivity approaches within a few per cent that of the bulk metal. Potassium and rubidium films, on the other hand, show a considerable excess of resistivity above that of the bulk metal, but it is shown that this excess is a residual resistance due to lattice strain, and that it may be partially removed by suitable annealing.

### 2. EXPERIMENTAL

The modified experimental tube is shown in fig. 1. Comparison with fig. 1 (Lovell 1936 *b*) shows that its essential features are the same as those of the previous tube, though there are considerable alterations of detail.

The cooled surface on which condensation takes place is the bottom of the long re-entrant pocket *J*, and the cooling bath *FF* has been extended upwards so as to enclose a considerable length of *J*. This construction allows the condensing surface to be brought closer to the pinhole *P*, and so permits of a much higher rate of deposition without raising the vapour pressure in

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the oven. In this way it was possible to deposit films of many thousand angstroms in thickness within a comparatively short period, and without the risk of the alkali metal attacking the pyrex-glass oven through raising the temperature. Further, the increased height of the cooling bath *FF* improves the heat insulation of the liquid nitrogen in *J*, and permits of long depositions without replenishing; a convenience when a liquefied gas is being boiled under reduced pressure.

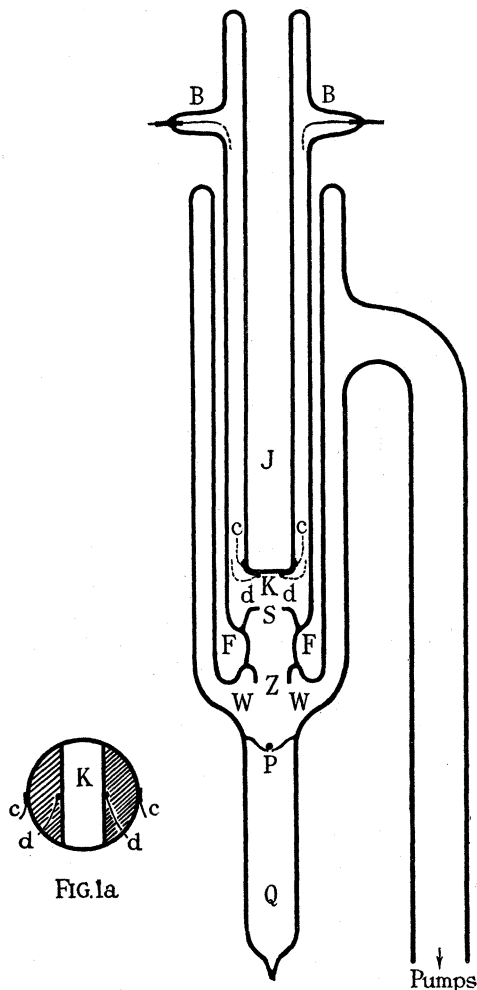


FIG. 1. The current leads *cc* and potential leads *dd* are brought out by four pinches around the periphery of the tube at *BB*.

The defining slit *S* was narrowed to 2.1 mm., so that the condensate now formed a narrow strip ( $2.6 \times 11.4$  mm.) overlapping the graphited contacts.

The effects of distortions of current flow where the current entered and left the film (due to possible unevenness of the graphite coating) were thus minimized. An additional subsidiary slit  $Z$  helped to cut down scattering from the walls  $WW$ .

The resistance of these thick films was very low compared with that of the end-contacts, and hence was measured by comparing the potential drop across the film with that across a standard resistance in series with it. The current leads  $cc$  were connected to the graphited edges of the surface  $K$  as shown in fig. 1  $a$ . The potential leads were attached by thin platinum wires  $dd$  to tiny glass beads fused to the surface  $K$  at the very edge of the graphiting. These beads were platinized and coated with graphite with the rest of the end-contacts as previously described (Lovell 1936  $b$ ).

In other respects the procedure of deposition and measurement was as described in the previous papers.

### 3. CALCULATION OF THE FILM RESISTIVITY

The width of the condensate was taken to be the mean width of the "umbra" and "penumbra" calculated from the geometry of the apparatus. With this particular slit system the overall width of the penumbra was 2.8 mm., of the umbra 2.4 mm., and it could readily be shown that the above approximation introduced a negligible error.

The length of the condensate was measured between the potential leads. In practice it proved impossible to place the potential leads on the geometrical edge of the graphited contacts, but measurements of the resistance of the graphiting indicated that no correction was needed on this account (at any rate for the thicker films). Where the film overlaps the graphiting the two are effectively in parallel, and the film resistance is very much lower than the resistance of the graphite undercoat.

The film thickness was calculated from the calibration of the beam as previously described.

### 4. RESULTS

Films of caesium, rubidium and potassium have been deposited on pyrex glass surfaces held at 64° K. The most significant results for these thick films are given in Table I. The values quoted for the bulk metal in this table are due to Hackspill (1910) (rubidium and caesium) and to Woltjer and Onnes (1924) (potassium).

Fig. 2 gives  $\frac{\text{Film resistivity}}{\text{Bulk metal resistivity}} \left( \frac{\rho}{\rho_n} \right)$  against film thickness  $t$  for

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TABLE I

	Bulk metal resistivity, $\rho_n$ ohm cm.	Film resistivity, $\rho$ ohm cm.	$(\rho_{90} - \rho_{64})$ bulk metal ohm cm.	$(\rho_{90} - \rho_{64})$ film ohm cm.
Caesium film thickness 10,280 Å	$4.00 \times 10^{-6}$	$4.15 \times 10^{-6}$	$1.36 \times 10^{-6}$	$1.30 \times 10^{-6}$
Rubidium film thickness 7220 Å	$2.00 \times 10^{-6}$	$2.80 \times 10^{-6}$	$0.60 \times 10^{-6}$	$0.68 \times 10^{-6}$
Potassium film thickness 2000 Å	$1.10 \times 10^{-6}$	$2.85 \times 10^{-6}$	$0.57 \times 10^{-6}$	$0.59 \times 10^{-6}$

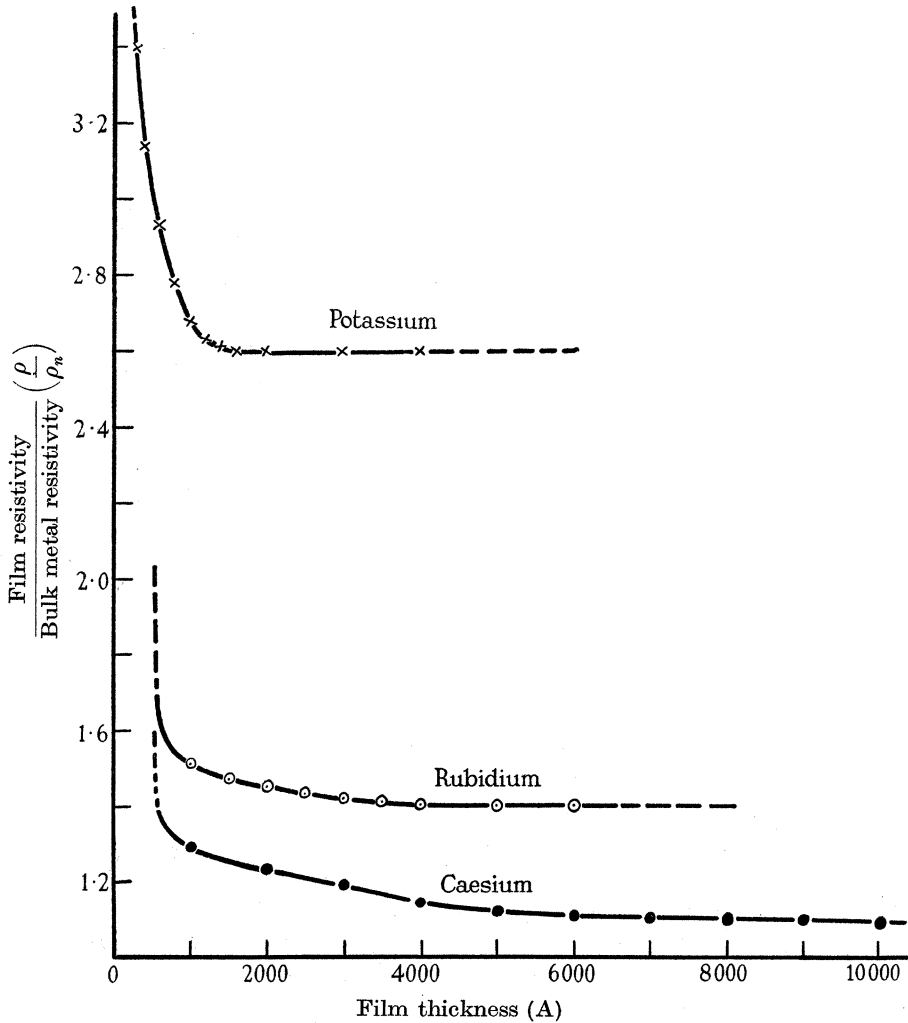


FIG. 2. Deposition of thick films of potassium (— x — x —), rubidium (— o — o —), and caesium (— • — • —) at 64° K.

$t > 500$  Å. (The resistivities of the thinner films have been given in the previous papers.)

In the deposition of the caesium film the resistivity decreases steadily with thickness and converges to a more or less constant value at about 10,000 Å, only 4 % in excess of that of the bulk metal. The change of resistivity in passing from 64 to 90° K. ( $\rho_{90} - \rho_{64}$ ) is perfectly reversible and almost identical with that of the bulk metal. In the case of rubidium the resistivity does not decrease appreciably after about 4000 Å and remains about 40 % greater than the value for the bulk metal. Potassium ceases to decrease in resistivity beyond 1600 Å, and its resistivity is more than double that of the bulk metal.

## 5. DISCUSSION

A comprehensive survey of the prominent factors influencing the resistance of metal films has recently been given by Appleyard (1937). There it is pointed out that films which agglomerate in their early stages of deposition must possess a finely polycrystalline structure, which may persist to great thicknesses. In such cases the condensate contains microcrystals possessing large surfaces of misfit, and the effect on the resistivity is to add a residual resistance to the normal value.

In previous work on the very thin films of the alkalis it has been shown that the initial layers increase in stability in the order: potassium, rubidium, caesium; and that at the lowest deposition temperature available (64° K.), the first layers of caesium are almost stable, while rubidium and potassium disintegrate considerably (Appleyard and Lovell 1937). On Appleyard's hypothesis we are thus led to expect quite a small residual resistance in the case of caesium, but successively greater for rubidium and potassium. Hence, we clearly have a highly probable explanation of the close agreement of the caesium film in Table I with the normal metal, and the greater disparity for rubidium and potassium.

One might attempt to explain the higher resistivity of the film material by assuming some form of geometrical disintegration of the film. The resistivity then obtained in these experiments would be merely a nominal value, say  $g$  times larger than the actual resistivity of the film material.  $g$  is a factor greater than unity and dependent only upon the degree of disintegration of the film. Thus the difference of resistivities between any two temperatures should also be  $g$  times the difference for the bulk metal, which is not consistent with experiment. Even if the cracks in the film are so close as to diminish the mean free path of the conduction electrons we should

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still expect the difference of the *absolute* resistivities to be greater than that for the bulk metal. We must therefore assume that these thick films differ from ordinary specimens of the metal only in being more finely polycrystalline.

There is one further observation strongly supporting this view. If the condensate really is an association of microcrystals, any annealing at a temperature higher than the temperature of deposition should result in a diminution of the film resistivity, due to relaxation in the surfaces of misfit (i.e. recrystallization). This has actually been observed consistently in these thick alkali films. For example, on the cessation of deposition at 64° K. a caesium film (10,200 Å) had a resistivity of  $4.33 \times 10^{-6}$  ohm cm. After being raised to 90° K. the subsequent resistivity at 64° K. attained a steady value of  $4.15 \times 10^{-6}$  ohm cm. After this initial change no further alteration occurred and the change of resistivity with temperature up to 90° K. was perfectly reversible. Attempts to anneal these films at much higher temperatures have been frustrated by semi-disintegration of the film (see Appleyard 1937).

A similar hypothesis of relaxation of strain in the lattice has been invoked by Suhrmann and Barth (1936), and by Vand (1937), to explain resistivity changes on annealing. Aggregations of microcrystals have also been found by Fujiwara (1932) in thin molybdenum films; and transformations from the slightly strained to the normal lattice on annealing by Ogawa (1937).

Quantitatively, the resistivities of films less than 100 Å in thickness showed good agreement with an expression derived from two assumptions: film thickness  $t \ll \lambda_0$ , the mean free path of the conduction electrons; and all collisions of the electrons with the boundaries of the film inelastic (Lovell 1936*b*).

Over most of the present range of thicknesses the effect of the shortening of the mean free path by collisions with the boundaries is relatively unimportant. However, Fuchs (1938) has recently developed a more general expression for the resistivity of thin films with different proportions of elastic scattering at the boundaries. In his paper (to which we refer for details) the experimental results for caesium have been compared with the generalized expressions over the range from 0 to 10,000 Å. The comparison suggests that the proportion of electrons scattered inelastically at the boundaries decreases from unity at very small thicknesses to about 0.3 or less at thicknesses greater than 150 Å.

To summarize this work on the alkali metals, we may say that apparently all the phenomena can be explained in terms of a few familiar physical ideas without invoking any of the numerous special hypotheses which have been

used by some previous workers in order to account for particular results (see Appleyard 1937 for bibliography). Finch (1937), reviewing experimental results on electron diffraction, likewise concludes that metal films on amorphous substrates do not differ fundamentally in structure from the normal metal. It seems possible therefore that a great deal of the inconsistency of previous work on other metals has been due to inadequate vacuum conditions and to insufficient attention to the surface condition of the substrate.

The majority of the work described here was carried out at intervals over an extended period in the H. H. Wills Physical Laboratory, University of Bristol, and the author is deeply indebted to Professor A. M. Tyndall for the necessary facilities, and to Dr Appleyard for invaluable advice. The author also desires to acknowledge the help given by Mr J. H. Burrow in the development of this high vacuum work, and his skill in the construction of the glass apparatus.

#### 6. SUMMARY

The technique previously described for measuring the electrical conductivity of thin films deposited by evaporation, in very high vacua, on clean substrates, has been modified to include the deposition of thick films of the alkali metals.

Caesium films 10,000 Å thick have resistivities only 4% greater than the bulk metal, and identical temperature coefficients. Thick rubidium and potassium films have rather higher resistivities, but possess the same temperature coefficients as the bulk metal.

Evidence is produced that the films are polycrystalline, and that the higher resistivities are due to a simple residual resistance. The gradation in properties of the thick films is shown to follow consistently from the properties of the very thin films investigated previously.

From these results and other considerations it is concluded that there are no grounds for the belief that thin films differ essentially in structure from the normal metal.

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## The dispersion formula for nuclear reactions

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### 1. INTRODUCTION

Bohr has shown that in a collision between two nuclei of which at least one is heavy, an unstable compound nucleus will be temporarily formed and that the lifetime of such a compound nucleus, measured on a nuclear scale, is usually very large. For this reason these compound nuclei have fairly well-defined energy levels (“virtual” or “resonance” levels), and the positions of these levels and the properties of the metastable states belonging to them determine the cross-sections for all nuclear reactions.

Breit and Wigner (1936) gave a formula for the probability of a nuclear reaction in terms of the virtual state, taking into account only one such state, while Bethe and Placzek (1937) and Bethe (1937) generalized the formula to take account of all possible virtual states. Their formula is usually referred to as the “dispersion formula” owing to its analogy with the formula for the dispersion of light by atomic systems.

In all these papers perturbation theory was used in order to derive the formula, and this involves the assumption that certain terms in the Hamiltonian of the nuclear system (such as the interaction between some of the constituents) may be considered as small, and that without these terms the virtual state would actually become stable. The perturbation theory was carried out only to the second order of approximation, and additional terms ought to arise when higher approximations are considered.