JOURNAL OF MATERIALS SCIENCE 16 (1981) 1661–1664

# Electrical size effect in polycrystalline vanadium films

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The electrical size effect of polycrystalline vanadium films evaporated onto molybdenum glass substrates at a temperature of 293 K was examined in vacuum at $10^{-10}$ Torr *in situ*. It has been shown that grain-boundary scattering and additional defects (absorbed foreign atoms) scattering are considerable and they cannot be neglected. On the basis of the electrical size effect the electron mean free path for the temperature range 293 to 575 K has been found to vary from $12.3 \times 10^{-10}$ to $7.7 \times 10^{-10}$ m.

## 1. Introduction

It is well known that thin metal films have higher resistivities than the bulk metal. This is a result of electrical external and internal size effects as well as a result of latice imperfections which are more pronounced in thin films. It follows that the mean free path of the conduction electrons is effected by many different factors. Determination of the electron mean free path from the size effect in films of various structures, requires that film conductivity models suitable for those structures be employed [1–4].

In the previous paper [5] it was shown that thin polycrystalline films of vanadium absorb gases. It, therefore, seems reasonable that a conductivity model must take into account not only the grain-boundary scattering but also the foreign atom scattering as well.

## 2. Experimental procedure

Thin vanadium films were grown on a molybdenum glass substrate at 293 K in the vacuum apparatus, UNI 5P, produced by Riber, by means of an electron gun. The vanadium used in the experiment was of high purity (Koch Light Laboratories). The evaporation processes were carried out in vacuum ($P = 1 \times 10^{-7}$ Torr) and the resistivity of films as a function of temperature was measured in a vacuum of $1 \times 10^{-10}$ Torr and higher. All the evaporation rates were comparable and were about 8 nm sec$^{-1}$. The temperature was measured by means of an iron–constantan thermocouple.

The evaporated films were 200 mm length, $l$, and 2 mm wide, $w$, as used in previous experiments [5]. An automatic measuring device was used to determine the resistance, $R$. The film resistivity, $\rho$, was derived from the relation

$$\rho = R \frac{dw}{l}. \quad (1)$$

The film thickness, $d$, was measured using the method of Tolansky [6]. The observed films had thicknesses ranging from 51.1 to 214.5 mm.

## 3. Experimental results

The resistivity of a series of vanadium films was examined in a vacuum of $10^{-10}$ Torr as a function temperature and thickness. The changes observed in the resistivities for the thinnest film and for the thickest film are presented in Figs 1 and 2. The experiment showed that the temperature dependence of the resistivity was the same for every film with $d < 85$ nm, as shown in Fig. 1, and for films with 214.5 nm $\geqslant d \geqslant$ 85 nm, as shown in Fig. 2.

Fig. 1 shows the resistivity as a function of temperature for films deposited onto a substrate at a temperature, $T_e$, of 293 K with an evaporation time, $t$, equal to 70 sec. The thickness was 51.1 nm. This film was annealed and cooled anternately; this cycle was repeated six times. The film resistivity after evaporation is represented by the point A; then the film resistivity decreased to point B; immediately after the film evaporation the pressure decreased to $2 \times 10^{-8}$ Torr and then

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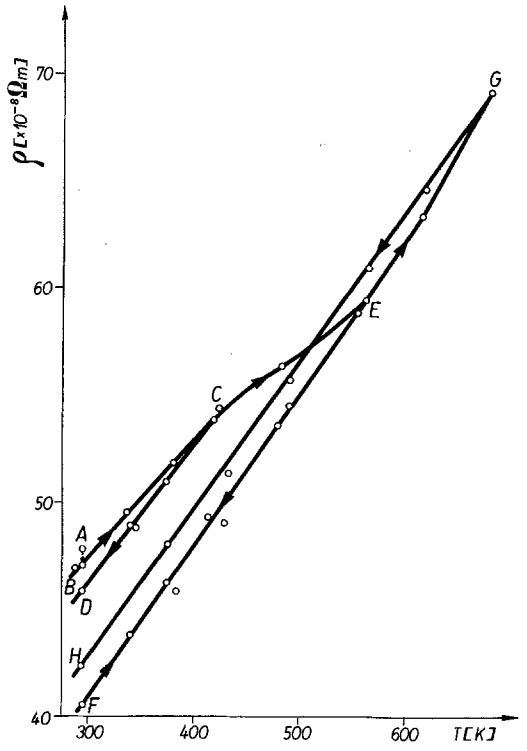


*Figure 1* The temperature dependence of resistivity for a film thickness, $d$, of 51.1 nm and a substrate temperature, $T_e$, of 293 K.

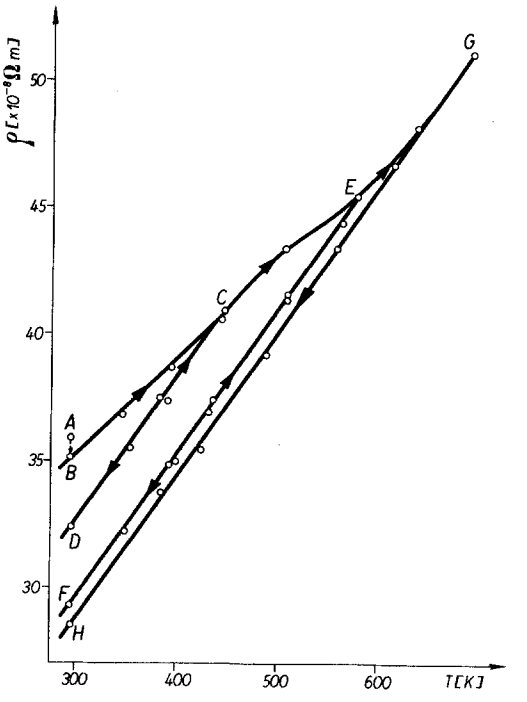


*Figure 2* The temperature dependence of the resistivity for a film thickness of 214.5 nm and $T_e$ of 293 K.

reached $8.5 \times 10^{-11}$ Torr; the line CD, illustrates both the cooling process (to 293 K) and part of the second annealing process (DCE to $T = 575$ K). The resistivity changes along CD exhibit reversible behaviour and a linear temperature dependence. The line EF illustrates the cooling process and part of the third annealing process (FEG to $T_a = 670$ K). The resistivity changes along EF are reversible and are linearly dependent on temperature. The line GH represents the last cooling process.

Fig. 2 shows the resistivity as a function of temperature for a film evaporated onto a substrate at $T_e = 293$ K with $t = 235$ sec. The thickness was 214.5 nm. This film was annealed and cooled in the same way as the film with $d = 51.5$ nm for which changes of resistivity with temperature are represented in Fig. 1.

The experimental values of $\rho d$ are plotted against $d$ for $T = 293$ K in Fig. 3. The experiments showed that the plot of $\rho d$ against $d$ was the same for any measuring temperature.

## 4. Discussion of the results

The electrical conductivity of metal films depends on many factors: for example, the disorder of crystalline lattice, which is due to the thermal motion of the lattice and to structural defects and additional defects (absorbed atoms of gases). The electron mean free path, $l_0$, which is one of the most important physical quantities, is associated with the electrical conductivity in metals. The electron mean free path depends not only on these factors. According to Ziman [7] for transition metals, which includes vanadium, s-electrons scattering on d-electrons must be taken into account.

Consideration of the size effect in polycrystalline metal films according to the Fuchs–Sondheimer theory [1, 2] documented by Mayadas and Shatzkes [3] and Wissmann [4] is not very precise. Mayadas and Shatzkes [3] and Wissmann [4] have independently studied the dependence of resistivity on thickness-dependent scattering at the crystalline boundaries. They have obtained the following expression for total resistivity

$$\rho = \rho_0 \left\{ 1 + [K'(1-p) + K] \frac{l_0}{d} \right\}, \qquad (2)$$

where $\rho_0$ is the resistivity of bulk material with the same defect density as the film, $l_0$ is the mean free path length corresponding to $\rho_0$, $d$ is the film

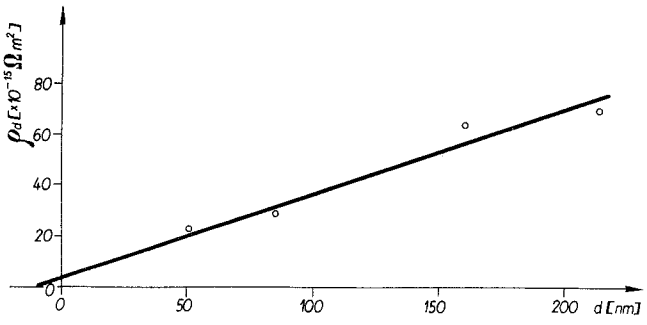


*Figure 3* The experimental $\rho d$ against $d$ for a film evaporated at a $T_e$ of 293 K.

thickness, $p$ is the fraction of electron specularly reflected from the surfaces, $K'$ is a constant and equals 3/8 in the Fuchs–Sondheimer theory and $K$ is a factor which takes into account boundary scattering.

We have added one factor to Equation 2. This factor, $K''$, takes into account scattering of electrons on additional defects. Equation 2 is then written as

$$\rho = \rho_0 \left\{ 1 + [K'(1-p) + K + K''] \frac{l_0}{d} \right\}. \quad (3)$$

If this equation is valid, a plot of $\rho d$ against $d$ should yield a straight line. From the slope and intercept of the line, $\rho_0$ and the value of $[K'(1-p) + K + K'']l_0$ can be obtained. Then, using the $\rho_0 l_0$ value (known from the literature) values of $l_0$ and $[K'(1-p) + K + K'']$ can be established.

Few studies on the electrical properties and size effect in vanadium films are reported in the literature. Most of them [8–15] have been carried out at liquid helium temperature. Chander *et al.* [13] have examined the size effect of vanadium films at room temperature in terms of the Sondheimer theory. Their results ($600 \times 10^{-10}$ and $1000 \times 10^{-10}$ m) are not highly probable according to the authors themselves.

TABLE I

| $T$(K) | $\rho_0$ ($\times 10^{-8}$ Ωm) | $l_0$ ($\times 10^{-10}$ m) | $[K'(1-p) + K + K'']$ |
|---|---|---|---|
| 293 | 31.1 | 11.3 | |
| 350 | 34.5 | 10.1 | |
| 400 | 37.4 | 9.4 | 18.6 |
| 450 | 40.4 | 8.7 | |
| 293 | 28.5 | 12.3 | |
| 350 | 31.9 | 11.0 | |
| 400 | 34.9 | 10.0 | |
| 450 | 37.9 | 9.2 | 16.8 |
| 500 | 40.8 | 8.6 | |
| 550 | 43.8 | 8.0 | |
| 575 | 45.2 | 7.7 | |

From our data for vanadium films it is evident that the films show a size effect. The character of the size effect is illustrated by the $\rho d$ against $d$ plot in Fig. 3. It is easily seen that this is a straight line. It follows that the size effect observed in vanadium films satisfies Equation 3. From Equation 3, $\rho_0$ and $[K'(1-p) + K + K'']l_0$ can be evaluated by the least-square fit method: hence using a $\rho_0 l_0$ value from the literature [16], $l_0$ and $[K'(1-p) + K + K'']$ can be calculated. The $\rho_0 l_0$ value was taken to be $3.5 \times 10^{-10}\,\Omega m^2$ after Radebanck and Keeson [16]. Our results are given in Table I and also in Figs 4 and 5.

It was found that the $\rho_0$ and $[K'(1-p) + K + K'']$ values decreased as the annealing temperature was increased (Figs 4 and 5, Table I). The decrease in $\rho_0$ is attributed to the disappearance of structural defects which is, in turn, accompanied by

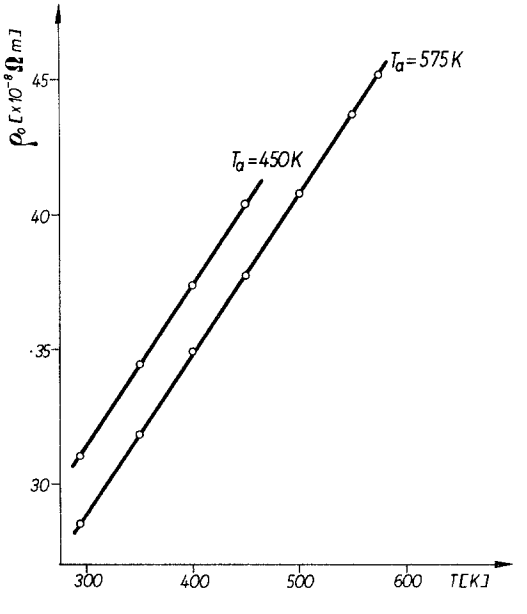


*Figure 4* The temperature dependence of $\rho_0$ for two annealing temperatures for vanadium films evaporated at a $T_e$ of 293 K.

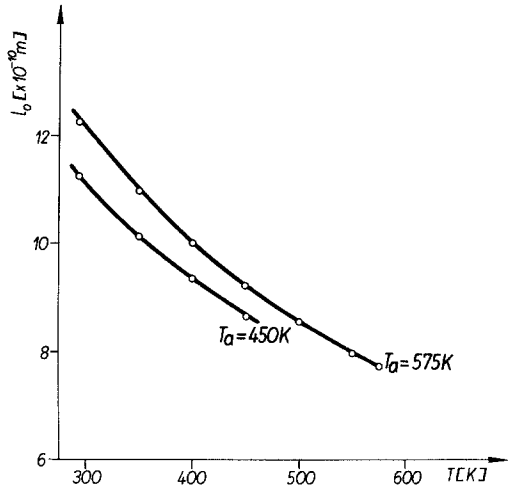


*Figure 5* The temperature dependence of the electron mean free path for two annealing temperatures in vanadium films evaporated at a $T_e$ of 293 K.

an increased in the electron mean free path (Fig. 5).

The electron mean free path values obtained in our experiments are less than those found by Chander *et al.* [13] because they analysed the size effect in terms of the Sondheimer theory and their films were evaporated at a pressure of $1 \times 10^{-5}$ Torr. Reale [11] found that the electron mean free path equals $47 \times 10^{-10}$ m at room temperature.

The mean free path determined on the basis of the work of Radebanck and Keeson [16] at room temperature equals $17.5 \times 10^{-10}$ m for vanadium monocrystal. Values of the mean free path for polycrystalline vanadium films obtained at room temperature by us are equal to $11.3 \times 10^{-10}$ and $12.3 \times 10^{-10}$ m for annealing temperatures of 450 K and 575 K, respectively. These values seem reasonable according to Radebanck and Keeson [16].

Values of $[K'(1-p)+K+K'']$ determined by us are 18.6 and 16.8 for annealing temperatures of 450 K and 575 K, respectively. Components $K$, $K''$ had unquestionable influence upon high values of $[K'(1-p)+K+K'']$. It is important to note that according to Wedler and Wiebauer [17], $K'$ can accept values greater than 3/8. The value of $[K'(1-p)+K+K'']$ decreases when the annealing temperature increases due to the disappearance of lattice defects and the growth of grains, which also results in the disappearance of structural defects.

## 5. Summary

(1) Thin vanadium films show the electrical size effect when they are obtained in ultra-high vacuum.

(2) Thin vanadium films absorb atoms of gases in ultra-high vacuum because the film resistivity increases and contributes to the electrical size effect.

(3) Experimental data on the resistivities of thin vanadium films show dependencies on thicknesses according to Equation 3.


## Acknowledgements

The study was sponsored by the Institute of Physics, University of Warsaw, Contract MR I-5.


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Received 13 November and accepted 4 December 1980.