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Base pressure effect on electrical properties of chromium nanofilms

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The thickness dependence of chromium films deposited onto a glass substrate is studied in the range 3.5–70 nm. Their electrical resistance grows with the base pressure during the deposition due to the scattering of electrons from impurities. The conduction electron mean free path is determined in the frameworks of Mayadas–Shatzkes theory.

Keywords: chromium films, pressure, electrical resistivity, Mayadas–Shatzkes theory, Fuchs–Sondheimer theory.

1. Introduction

Among all the metals, chromium is known as one of the best metals for fabricating thin-film resistors. It is also used as an underlayer in many electronic devices, which helps to provide a good adherence for other thin films and is frequently utilized for the preparation of semi-reflection coating and pre-coating for optical mirrors [1]. Apart from this, chromium has many attractive characteristics, such as low electrical conductivity, compared to other metals [2], the temperature dependence of resistance is low compared to tin and silver, its melting point is high compared to other metals such as tin and silver, high resistance, melting point, high resistance to corrosion, high sticking coefficient, and negative Seebeck coefficient [3].

2. Theoretical section

The accurate study of the size effect was worked out by Fuchs by solving Boltzmann's transport equation [4–6], along with appropriate boundary conditions. He obtained an expression for thin films' electrical resistivity ρ as

$$\rho = \rho_0 \left[1 + \frac{3}{8} \frac{(1-p)}{\lambda} \right], \ \lambda > 0.1, \qquad (1)$$

where ρ is electrical resistivity of the film, ρ_0 is resistivity of infinitely thick film, p is specularity parameter, $\lambda = t / l$, where t is the film thickness, l is conduction electron mean free path.

Equation (1) is known as Fuchs–Sondheimer (FS) theoretical equation for electrical resistivity of thin nanofilms. This expression for the resistivity is valid for chromium films with a thickness of more then 30 nm. However, Fuchs's theory did not consider the scattering of electrons at grain boundaries, which prevails in very thin films. Mayadas–Shatzkes (MS) modified Fuchs's theory by taking into account grain boundary scattering and obtained an expression for resistivity [7] as

$$\rho = \rho_0 \left[1 + \frac{3}{8\lambda}(1-p) + \frac{3}{2}\alpha' + ... \right], \qquad (2)$$

where α' is the grain boundary scattering power, which is different for different film thicknesses in the lower thickness range.

The difference of Eqs. (1) and (2) gives the value $(3/2)\,\rho_0 \times \alpha'$ is the resistivity due to grain boundary scattering, which is predominant in the lower thickness region, as in the present case ($t < 30$ nm). The difference of Fuchs theoretical and (MS) experimental curves at each deposition base pressure provides the value of $(3/2)\,\rho_0 \times \alpha'$.

3. Experimental technique

Prior to chromium deposition, the glass substrates were subjected to a series of cleaning steps. Initially, the glass substrates were cleaned using chromic acid. Then, cleaned substrates were again cleaned with distilled water and acetone to remove greasy substances adhered to the substrate and washed using an ultrasonic cleaner that contains detergent water at 50 °C. Finally, the substrates were rinsed with distilled water in the ultrasonic cleaner tank.

Before deposition, the substrate was additionally cleaned by ionic bombardment. The film thickness was determined using a digital quartz crystal thickness monitor housed in a vacuum chamber above the evaporation source and by measuring deposition rate in a vacuum.

Chromium nano-films were grown by thermal evaporation in a vacuum of $2\cdot10^{-6}$ Torr onto cleaned glass substrates, at room temperature 22 °C [8, 9]. The distance between the substrate and evaporation source was around 0.22 m. The deposition rate was 0.2 nm/s [10]. We used for evaporation chromium of 99.99 % purity, imported from Leico industries, New York, USA. The tungsten filament in which the source Cr material was placed served as a Joule's heating evaporator, and condensation of the chromium film was made onto the glass substrate.

The substrate was placed on the sample holder metal disc and mounted in the vacuum chamber. For in-situ resistance measurements, we used a four-probe technique with copper wires connected to the sample through indium. The four metal tips were part of an auto-mechanical stage with typical probe spacing ~ 2 mm, which moves up and down during measurements. A high impedance constant current source with ammeter was used to supply current, and a voltmeter measured the voltage across the inner two probes to determine the sample resistivity.

4. Results and discussion

4.1. Effect of base pressure on electrical properties

Pressure has a strong influence on morphology, texture, brilliancy, and transport characteristics of chromium films, which was the basis for the research undertaken. Figure 1 shows the change in the specific electrical resistivity of Cr films depending on the thickness in the range (3.5–70) nm, deposited at $2\cdot10^{-6}$ and $2\cdot10^{-5}$ Torr, base pressures. The saturated values of resistivity of the films grown in a 10^{-6} and 10^{-5} Torr vacuum are $60\cdot10^{-8}$ Ohm·m and $132\cdot10^{-8}$ Ohm·m, respectively. Figure 1 also shows the calculated resistivity, using Fuchs's theory, for our experimental chromium films deposited at pressures of $2\cdot10^{-6}$ and $2\cdot10^{-5}$ Torr.

Figure 2 shows the plot of ρt *vs* t based upon Eq. (1). The asymptotes of the experimental curves in Fig. 1 at $t \to \infty$ gives the value ρ_0 for each pressure. The intercepts of the straight lines on the ρt axis in Fig. 2 give the values of $(3/8)\rho_0 l(1-p)$ for films deposited at each base pressure. Hence we can evaluate the values of $l(1-p)$, l, and p presented below in Table 1. The best fits were obtained at $p = 0.3$ and 0.1 for the films deposited at 10^{-6} and 10^{-5} Torr, respectively.

Pressure is considered as one of the essential parameters of deposition. It significantly changes the purity as well as the electrical properties of film coatings. As seen from Table 1, the infinitely thick film resistivity (ρ_0) rises with

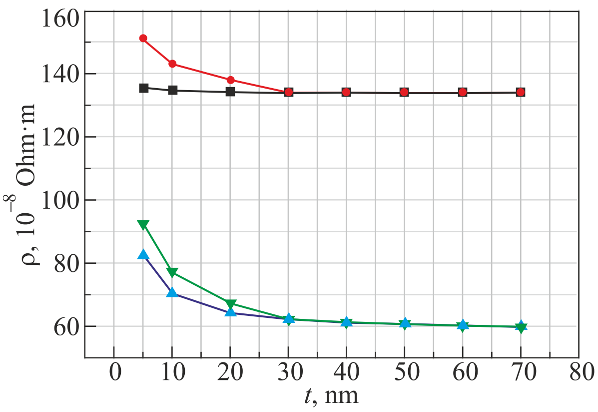

Fig. 1. (Color online) Experimental dependencies (●, ▼) on the thickness t of the resistivity ρ of Cr films obtained at base pressures of $2\cdot10^{-6}$ (▼) and $2\cdot10^{-5}$ (●) Torr and their fitting (■, ▲) using the FS theory.

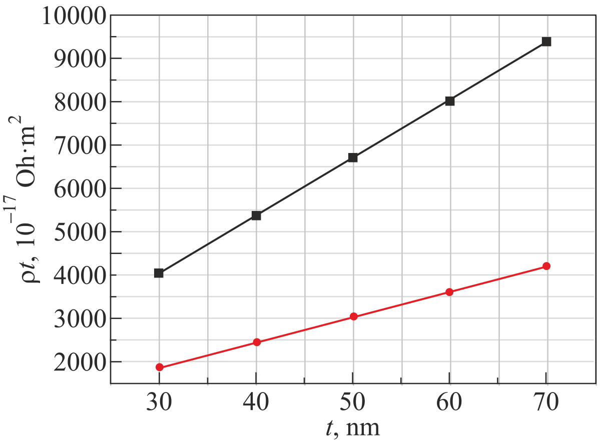

Fig. 2. (Color online) Experimental dependences of ρt on the thickness t for Cr films obtained at base pressures of $2\cdot10^{-6}$ (●) and $2\cdot10^{-5}$ (■) Torr. The best linear approximations $y = mx + c$ are achieved at $m = 133.82$, $c = 6.2$ (■) and $m = 58.38$, $c = 120.8$ (●).

Table 1. Electrical parameters of chromium films, in accordance with Eq. (1), obtained at two base pressures

Sample series No.	Material	Pressure, Torr	$\rho_0\cdot10^8$, Ohm·m	$l(1-p)$, nm	l, nm	p
1st	Chromium	$2\cdot10^{-6}$	58.3	5.5	7.8	0.3
2nd		$2\cdot10^{-5}$	99.99	2.07	2.30	0.1

enhancing pressure due to the incorporation of defects (impurities) during the film growth. Ultimately this leads to a large resistivity for chromium films grown at higher pressures and decreases the value of *l*. Table 1 indicates that the *p*-value decreases with increasing pressure, which means that diffuse scattering of conduction electrons in thin Cr films is enhanced. Similar increase in corrosion resistance, in case of Al sputtered thin film was reported with increase of base pressure by G. S. Frankel [11].

5. Conclusion

The electrical resistivity of two series of thin chromium films obtained by thermal evaporation in vacuum at base pressures $2\cdot10^{-6}$ and $2\cdot10^{-5}$ Torr has been studied. According to Table 1, the *p*-value decreases with increasing pressure in the vacuum chamber during deposition, which reflects the enhancement of diffuse scattering of conduction electrons in thin Cr films.

The experimental data analyzed in the frameworks of Mayadas–Shatzkes and Fuchs–Sondheimer theories for electrical resistivity versus film thickness $\rho = f(t)$ curve. The calculated values of the electron mean free path *l* for the base pressure $2\cdot10^{-5}$ Torr is less, while the resistivity ρ_0 of the metal is, respectively, higher, compared to the films grown in $2\cdot10^{-6}$ Torr base pressure, because of more impurity scattering center embedded in the film grown in a bad vacuum.

The authors also wanted to draw attention to the fact that in [11], G. S. Frankel reported an increase in the corrosion resistance of thin aluminum films with an increase in the base pressure during deposition.

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Вплив залишкового тиску на електричні властивості наноплівок хрому

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Вивчено залежності властивостей хромових плівок, які осаджені на скляну підкладку, від товщини у діапазоні 3.5–70 нм. Спостережено зростання їх питомого опору з ростом залишкового тиску при осадженні, що пов’язано із розсіянням електронів на домішках. Довжина вільного пробігу електронів провідності визначалася в рамках теорії Мейядеса–Шацкиса.

Ключові слова: хромові плівки, електричний питомий опір, теорія Мейядеса–Шацкеса, теорія Фукса–Сондгеймера.