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Variation in Thickness of Copper Films Deposited at Various Distances and Angles Using the Thermionic Vacuum Arc

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Abstract

The thermionic vacuum arc (TVA) is a new technique for the deposition of thin metallic films. Copper depositions were made on glass substrates placed at various distances and angles with respect to the TVA source. By measuring the thickness of the film on each substrate, the variation in the thickness as a function of the distance and angle with respect to the TVA source is investigated.

Key Words: Deposition, anodic vacuum arc, copper vapor plasma, thickness.

1. Introduction

The lack of mobility associated with low energy depositions such as via electron beam evaporation, frequently results in a poor density coating filled with voids and impurity atoms [1, 2].

Arc discharge-based processes produce positive ions, which can be accelerated onto the film substrate to be coated, with increased atomic mobility that can result in improved film properties [3, 4, 5]. For example, adhesion strength, packing density, surface roughness, crystalline state and structure of the deposited films are improved remarkably by the acceleration of the ionized particles [5].

The well-known vacuum arc, i.e. the cathodic vacuum arc; though is frequently employed to do metal vapor deposition, is plagued by cathode spots [6]. Cathode spots are small, bright and intense current concentrations at the cathode moving rapidly and randomly over the surface of the cathode [7]. Thus, with respect to coating applications, a major disadvantage of this arc is the production of numerous macroparticles in the cathode spots [8, 9].

Anodic arcs are sustained by material evaporating from a hot anode and can be classified according to the means by which electrons are supplied. These can be hot filaments [10, 11] or hollow cathodes in the presence of a process gas [12, 13, 14, 15]. A simpler form of the anodic evaporation vacuum arc source has been described in Refs. [16, 17, 18]. In this method, a cooled cathode operating in the cathode spot mode is mounted opposite to an anode which contains the material to be evaporated. The advantage of this type of arc is the absence of macroparticles which are produced by the cathodic arcs [19].

The thermionic vacuum arc (TVA) is a new type of anodic arc. The TVA discharge is established between a heated cathode and an anode containing the material to be evaporated and produces a pure, gas- and macroparticle-free metal vapor plasma for nearly every metal [20, 21, 22, 23].

We constructed a TVA system at our university in the year of 2000. The vacuum vessel, the power supply system, and the electrodes of system were all designed and built using in-house facilities. The vacuum pumps and pressure measurement devices were purchased from the manufacturers. In this study, results are

presented concerning the variation in the thicknesses of copper films deposited onto glass substrates having positions at various distances and angles with respect to the TVA source.

2. Experimental Arrangement

A schematic presentation of the TVA electrode arrangement for an interelectrode angle $0^o < \varphi < 90^o$ is shown in Figure 1.

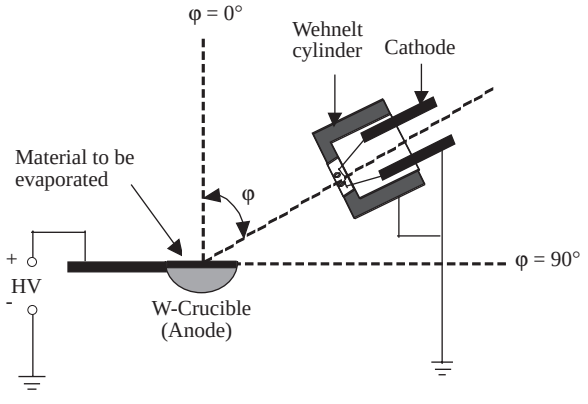

Figure 1. Schematic diagram of the TVA electrodes arrangement for $\varphi > 0^o$. The electrodes (cathode and anode) can be arranged in various relative angular positions φ and distances d to the anode. d is the distance between the front surface of the Wehnelt cylinder and the end side of the crucible for the case $\varphi = 90^o$. The notation HV indicates the high voltage power supply.

The TVA discharge is produced under vacuum conditions between a heated cathode emitting themoelectrons and an anode containing the material to be evaporated. The cathode is formed of 4 loops of 0.4 mm diameter tungsten wire wound to a 1 mm inner diameter. This filament is mounted inside a Wehnelt cylinder with a 5 mm diameter hole at the front. The Wehnelt cylinder has a diameter of 12 mm and length of 15 mm. The cathode-filament is heated directly and the entire cathode can be arranged in various relative positions and distances with respect to the anode. As shown in Figure 1, the angle φ between anode and cathode can be changed. The anode is made from 0.2 mm thick tungsten and has the shape of a spoon with an upper side diameter of 10 mm. The material to be evaporated is placed into this spoon-type crucible.

Both electrodes are mounted on a table which is placed inside a vacuum chamber kept at about 10^{-5}–10^{-6} mbar. The electrodes are connected to a DC high voltage power supply (10 kW, 0–5 kV). The discharge current is controlled by a 300Ω ballast resistor and adjustment of DC high voltage.

After applying a current I_f to the cathode filament and ensuring thermoelectronic emission of the cathode, a high voltage is applied across the electrodes. The thermoelectrons emitted by the cathode are focalised by the Wehnelt cylinder, which is connected to ground, and accelerated toward the anode by the applying high voltage. As the thermoelectrons bombard the anode, the anode material is heated; above some temperature the material starts to evaporate. Increasing the applied voltage beyond some point causes a bright discharge between the electrodes. The spectral characteristics of this discharge shows that it takes place in pure anode material vapor [24]. This metal vapor plasma continuously expands away from its source, the anode. Evaporated material can be deposited on a substrate by placing it above the TVA source (anode).

In the present experiment, glass substrates mounted inside a metal holder positioned at various distances and angles with respect to the TVA source (anode). By evaluating the mass differences before and after deposition, we obtained the mass of the deposited thin copper film on each substrate. Hence, the variation in the thickness as a function of the distance and angle with respect to the TVA source was determined.

3. Experimental Results

In order to investigate copper film thickness variations with deposition distances, copper films were deposited onto glass substrates of 20 × 76 mm size with a thickness of 1 mm placed at various distances from the TVA source (anode) in the z direction, with $\phi = 0^o$ (see Figure 3). Before deposition, the glass substrates were individually cleaned in an ultrasonic bath of citric acid, dried in an oven 150 °C at temperature and weighed. Once a glass substrate was placed at the selected distance from the TVA source (anode), and the vacuum chamber was pumped down, the TVA discharge in copper vapor was established, exposing the glass substrate to the copper vapor plasma. Similar procedures were repeated for various distances at $\phi = 0^o$. Since all depositions can not be obtained in the same run, the experimental conditions were kept identical for each run. The copper vapor TVA discharges for each deposition were established for the following conditions: Cathode filament current $I_f = 13$ A, interelectrode angle $\varphi = 90^o$, interelectrode distance d = 2 mm, and mass of the material (copper) to be deposited m = 0.1 g. The arc current varied between 100 and 120 mA during depositions.

The glass substrates with the deposited copper film were weighed after deposition. The mass of the deposition on the glass substrates was calculated by computing the difference in the mass of the substrate before and after deposition, and was evaluated within a maximum error of ± 0.1 mg. The thickness of the film over each substrate was assumed to be uniform, and the average thickness of the film on each substrate was calculated via the relationship

$$h = \frac{\Delta m_n}{S \cdot \rho_{Cu}}, \tag{1}$$

where $\rho_{Cu} = 8.11$ g/cm^3 is the density of copper, Δm_n is the mass of the film, and S is the surface area of the film. In most cases, the density of thin film is not equal to the density of the bulk material. But, the density of thin films obtained bombarding during deposition with ions is close to that of the corresponding bulk material [25]. The TVA generates a metal vapor plasma with a high degree of ionization, up to 20% [23]. Therefore, in this study it was given that the density of copper film is equal to the density of bulk material. Deposited thin film thicknesses vs. distance from the TVA source are given in Table 1.

Table 1. Variation in the thickness of the copper films deposited on various distances from the TVA source for $\phi = 0^o$.

Vertical deposition distance (mm)	Experimental thickness (μm)	Calculated thickness (μm)
20	2.840	2.840
30	1.110	1.262
40	0.706	0.71
50	0.543	0.454
60	0.362	0.314

As seen in Table 1, as the distance of the sample to the TVA source increases, the film thickness decreases due to the decreasing copper vapor density. The thicknesses of the films h listed in the third column in Table 1 are calculated using

$$h = C_1 \frac{1}{r^2}, \tag{2}$$

where r is the deposition distance and C_1 is a constant. In Table 1, experimental and calculated thicknesses for vertical deposition distance $r = 20$ mm were assumed to be equal. A normalization constant was obtained using Eq. (2): $C_1 = 1136$. This value was applied to the other calculated thicknesses in the last column in Table 1. The relation between experimental thicknesses and calculated thicknesses for $\phi = 0^o$ is shown in Figure 2.

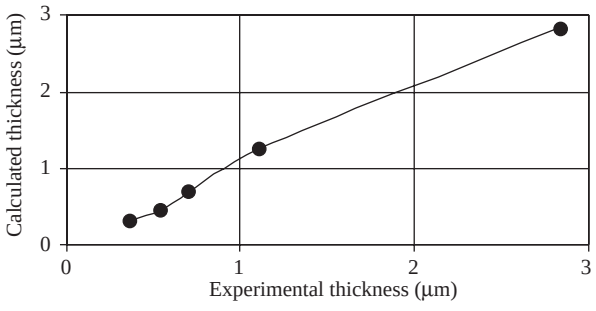

Figure 2. The relation between experimental thicknesses and calculated thicknesses for depositions at various distances at $\phi = 0^o$.

The linear dependence observed in Figure 2 proves that experimental results are in agreement with the calculated results. Consequently, the dependence of the thickness on the deposition distance is well described by Eq. (2).

We repeated similar procedures in order to investigate the variation in the thickness as a function of the distance and angle with respect to the TVA source (anode). For this purpose, 8 glass substrates of 10 x 20 mm with a thickness of 1 mm were all inserted inside a metal holder of 20 x 200 mm. This metal holder and slides were placed 140 mm from the TVA source, as shown in Figure 3.

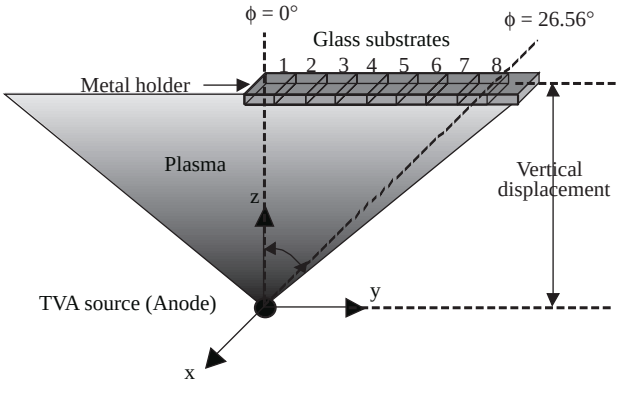

Figure 3. Experimental arrangement for the deposition on glass substrates at various angles and distances with respect to the TVA source (anode).

The glass substrates were individually cleaned, dried, and weighed and recorded as substrates m_1, m_2,.....,m_8 prior to inserting them into the metal holder. The numbers in Figure 3 indicate the order of the glass substrates in the metal holder relative to $\phi = 0^o$. In Figure 3, $\phi = 0^o$ corresponds to the line from the TVA source to the midpoint of substrate number 1. ϕ is the angle between this line and the lines connecting the TVA source to the midpoints of the other substrates. After the glass substrates were placed at various angles and distances with respect to the anode and the vacuum chamber was pumped down, the TVA discharge in copper vapor was established, exposing the glass substrates to the copper vapor plasma. The operational parameters were as follows: Cathode heating current I_f = 13 A, interelectrode angle $\varphi = 90^o$, and the interelectrode distance d = 2 mm. During deposition, the arc current was kept at a constant value of 180 mA. After deposition, the 8 glass substrates with the deposited copper films were weighed again and recorded as $m\prime_1$, $m\prime_2$,....., $m\prime_8$. The mass of deposition on the glass substrates was calculated by computing the difference in the mass of the substrates before and after deposition, i.e. $\Delta m_n = m\prime_n - m_n$, and was evaluated within a maximum error of ± 0.1 mg. The thickness of the film over each substrate was assumed to be uniform, and the average thickness of the film on each substrate was found using Eq. (1). Experimental results are given in Table 2. In Table 2 is also given the calculated values of the thickness from Eq. (3). The expression used for the calculated thicknesses in Table 2 is given by

$$h = C_2 \frac{\cos\phi}{r^2}, \tag{3}$$

where ϕ is the deposition angle, r is the deposition distance, and C_2 is a constant. Similar to the case in Table 1, a normalization constant, $C_2 = 16098$, was obtained using Eq. (3), and was applied to the last column in Table 2.

Table 2. Variation in the thickness of the copper films deposited on various angles and distances with respect to the TVA source. (Distance from the TVA source to the center of the substrate number 1 at $\phi = 0^o$, 140 mm).

Substrate number	Deposition distance r (mm)	Deposition angle ϕ (degrees)	Experimental Thickness (μm)	Calculated thickness (μm)
1	140	0.00	0.821	0.821
2	140.35	4.08	0.771	0.814
3	141.42	8.13	0.652	0.795
4	143.17	12.09	0.598	0.766
5	145.60	15.94	0.544	0.729
6	148.66	19.65	0.491	0.684
7	152.31	23.19	0.428	0.637
8	156.52	26.56	0.301	0.585

As seen in Table 2, the thickness of the film deposited on the glass substrates placed at $\phi = 0^o$ relative the TVA source is highest, while the thicknesses of the films deposited on the glass substrates placed at $\phi > 0^o$ decrease with increasing ϕ. The results given in Table 2 show that the experimental results are not in full agreement with the calculated results, especially at large values of ϕ. We suppose that this is because the TVA source cannot, in reality, be modeled as a point source with a uniformly hemispherical distribution, as is tacitly assumed in Eq. (3).

4. Conclusion

The thickness of copper films deposited on glass samples changes with deposition distances and angles with respect to the TVA source. The experimental results are in agreement with the calculated results for various distances, but are not in full agreement with the calculated results for depositions at various distances and angles, especially for large deposition angles.

References

[1] K.H. Müller, *J. Appl. Phys.*, **59(8)**, (1986), 2803.

[2] J.A. Thornton, *J. Vac. Sci. Technol.,* **11**, (1974), 666.

[3] D.M. Sanders, *J. Vac. Sci. Technol. A*, **7**, (1989), 2339.

[4] P. Martin, *IEEE Transactions on Plasma Science*, **18**, (1990), 885.

[5] T. Takagi, *Thin Solid Films*, **92**, (1982), 1.

[6] W.D. Davis and H. C. Miller, *J. Appl. Phys.*, **40**, (1969), 2212.

[7] D.Y. Fang, *J. Phys. D*, **15**, (1982), 833.

[8] J.E. Daalder, *J. Phys. D*, **9**, (1976), 2379.

[9] H. Randhawa, *Thin Solid Films*, **153**, (1987), 209.

[10] R. Buhl, E. Moll, and H. Daxinger, U.S. Patent No: 4 448 802, (1984).

[11] H.J. Hamilton, French Patent No: 1 496 697, (1967).

[12] A. M. Dorodnov, A.N. Kuznetsov, and V.A. Petrosov, *Sov. Tech.-Phys. Lett.,* **5**, (1979), 418.

[13] V.A. Saenko, A.I. Vladimirov, G.N. Veremeichenko, and V.A. Kravatski, *Instrum. Exp. Tech.* (USSR), **28**, (1985), 234.

[14] C. Schalansky, Z.A. Munir, and D.L. Walmsley, *J. Mat. Sci.*, **22**, (1987), 745.

[15] D.G. Williams, *J. Vac. Sci. Technol.* **11**, (1974), 374.

[16] H. Ehrich, *J. Vac. Sci. Technol.*, **6**, (1988), 134.

[17] H. Ehrich, B. Hasse, K.G. Müller, and R. Schmidt, *J. Vac. Sci. Technol.*, **6**, (1988), 2499.

[18] H. Ehrich, *Vacuum-Technik*, **37**, (1988), 176.

[19] D.M. Sanders, D.B. Boercker and S. Falabella, *IEEE Trans. On Plasma Sci.*, **18**, (1990), 883.

[20] G. Musa, H. Ehrich, and M. Mausbach, *J. Vac. Sci. Technol. A*, **12(5)**, (1994), 2887.

[21] H. Ehrich, J. Schuhmann, G. Musa, A. Popescu, I. Mustata, *Thin Solid Films*, **333**, (1998), 95.

[22] H. Ehrich, G. Musa, A. Popescu, I. Mustata, A. Salabas, M. Cretu, G.F. Leu, **343-344**, (1999), 63.

[23] G. Musa, H. Ehrich, J. Schuhmann, *IEEE Transactions on Plasma Science*, **25**, (1997), 386.

[24] G. Musa, A. Baltog, A. Popescu, N. Betiu, I. Mustata, *Contr. Plasma Phys.,* **26(3)**, (1986), 171.

[25] S.M. Rossnagel and J.J. Cuoma, *Thin Solid Films*, **171**, (1979), 143.