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THERMOIONIC VACUUM ARC – A NEW METHOD OF THIN FILM DEPOSITION

R. Vladoiu[a], G. Musa[a, b] I. Mustata[b*]

[a]Department of Physics, Ovidius University Constanta, 8700, Romania
[b]National Institute for Laser, Plasma and Radiation Physics, Bucharest/Magurele, Romania

New equipment for the technology of thin film deposition using thermoionic vacuum arc is presented. Advantages of this system are underlined: extended application possibilities for the increase of the microhardness of the pieces, decrease of the friction of moving pieces, change of the chemical reactivity of the pieces (corrosion resistant components). The new technique can be used for the development of nanostructural materials.

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1. Introduction

The peculiarity of the development of the high tech area researches in the last decades was without doubts, the continuous miniaturization both of the final products as well as its parts. Micron size elements and, more than this, nanostructured materials started to be real dimensions of the components on production lines.

Of course, such changes have imposed also a change in the field of related technologies. New requirements have appeared for the produced thin films, which must be extremely smooth, very compact, having good tribological properties and also strong mechanical and chemical resistance.

We can say that a new generation of equipment have also been created to fulfill this new requirement of the near future products. One of the developed new technology for thin film deposition is Thermionic Vacuum Arc (TVA), which is already operational. In this paper we present this new technology recently promoted at Ovidius University, Constanta.

2. Experimental

Thin film deposition process by Thermionic Vacuum Arc (TVA), a new discharge type in pure metal vapor plasma, can become one of the most suitable technology to significantly improve the quality of the surfaces covered with different materials using present technologies.

Thermionic Vacuum Arc can be ignited in vacuum (or UHV) between a heated cathode surrounded by an electron focusing Whenelt cylinder and an anode (tungsten crucible) containing the material to be deposited. Due to the electron bombardment of the anode by the accelerated thermo-electrons from the grounded cathode towards the anode (which is at high voltage), anode material first melts and afterwards starts to evaporate ensuring a steady state concentration of the evaporated atoms in the cathode – anode space. At further increase of the applied high voltage, a bright discharge is established inside of the vacuumated vessel in the vapors of the anode material. In Fig. 1 it is schematically shown the disposal of the TVA electrodes.

* Corresponding author: mustata@alpha1.infim.ro

As cathode is used a simple electron beam gun, which consists in a tungsten filament mounted inside of a Whenelt cylinder. The cathode can be mounted in various positions against the anode. These positions are defined by the angle φ.

The anode is a tungsten crucible with a spoon like shape. The crucible is filled up with particles of the material to be evaporated in the present experiment copper. The electrodes assembly is mounted in a vacuum vessel.

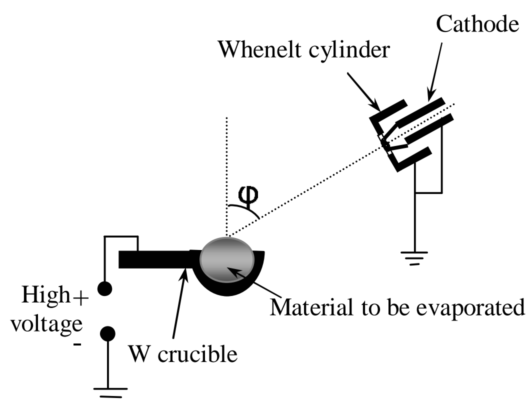

Fig. 1. The TVA electrodes arrangement.

The high vacuum vessel having a diameter of 400 mm and a length of 450 mm is provided with a turbomolecular pumping down system coupled with a mechanical pump, ensuring an end pressure in the vessel lower than 10^{-6} Torr.

For a convenient applied D.C. high voltage over the cathode and anode space, a melted spot appears on the anode surface and a continuous evaporation of the anode material from this melted spot is established due to the accelerated electrons emitted from the cathode. A steady state density of the metal vapors appears in the inter-electrode space.

At further increase of the applied high voltage, suddenly a bright discharge of green color appears in the inter-electrode gap, with a simultaneous decrease of the voltage drop over the discharge and a significant increase of the arc current. The discharge is stable in shape, electric current value and the emitted light intensity.

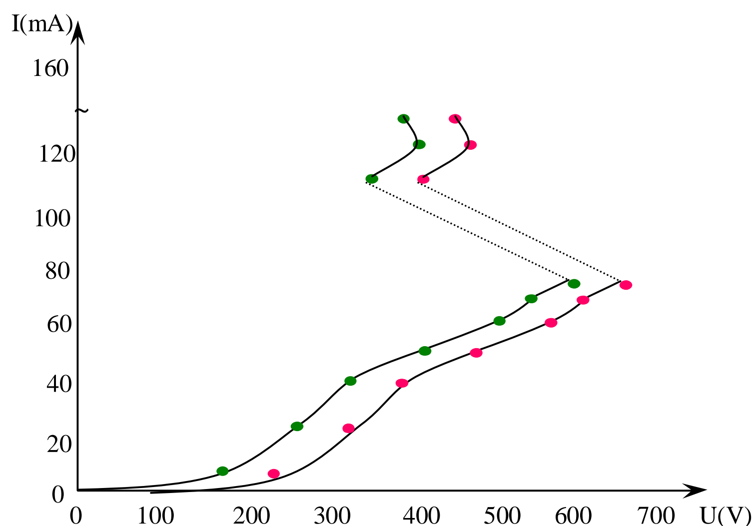

Fig. 2. The volt–ampere characteristics for TVA.

The volt-ampere characteristics for R = 1 kΩ and R = 1.5 kΩ are shown in Fig. 2. For low discharge currents and voltages, the characteristics are identical with those of the vacuum diodes. At certain level of the applied voltage, which depends on the heating current I_f, a sudden increase of the current can be observed. The sudden increase is correlated with the ignition of a bright metal vapor discharge between electrodes.

We will consider TVA as being in arc regime, for the range of volt-ampere characteristics for which we have low arc voltage drop, bright light emission and increased discharge current.

Any change of the parameters' values: distance between electrodes, angle φ, or cathode heating current I_f, will change the value of the arc voltage drop over the electrodes.

3. TVA deposited thin film qualities

The analyses of the deposited 1 μm thickness of copper thin films on Si wafer, glass plates and plastic pieces have shown the good quality of the films. SEM analysis with 20000 magnification has proved smooth surfaces without droplets. The droplets usually appear at arc deposition. In our case, because the evaporation of material to be deposited is not coming from cathode but boiling anode material (copper in tungsten crucible), no droplets was observed.

The SEM pictures taken on cross-sections of copper film have evidenced that the deposited film is compact without any columnar structure.

Because the filament of the cathode was situated inside of a tungsten (wolfram) Whenelt cylinder and away from the copper plasma positioned at anode surface, no wolfram impurities have been observed. Also, because after arc ignition copper is easily boiling (at temperatures much lower than for tungsten), no impurities can be generated from the crucible.

XPS analysis of the deposited copper thin films using Thermionic Vacuum Arc at Institut fur Spectrochemie and Analytical Spektroscopy Dortmund have not detected W in the deposited copper films.

Due to the copper plasma ion bombardment of the sample on which copper films was just depositing has proved strong adhesion of copper film to plastic pieces. Moreover, it was established a linear correlation between adherence of the copper film on plastics and the energy of ions in the copper plasma as can be seen in Fig. 3. The used method was submission of probes to ultrasonic cavitation, a method developed at Essen University.

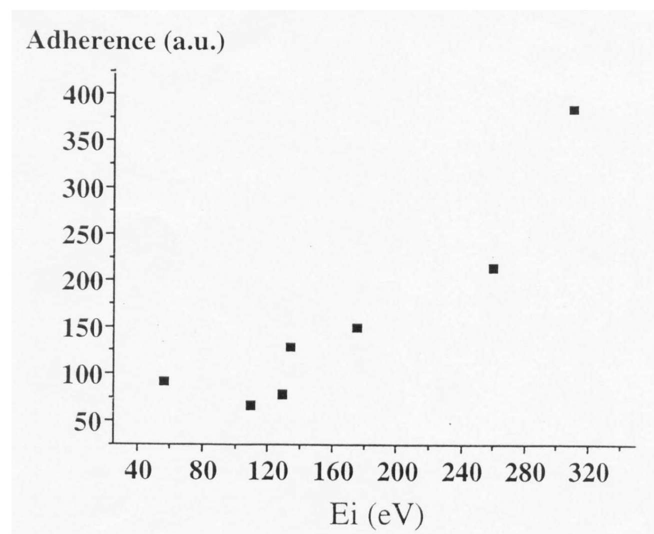

Fig. 3. Dependence of the adherence of copper film on plastic substrate on the energy of ions.

Fig. 3 shows the dependence of the adherence of the deposited copper film on plastic foils versus the value of the directed energy of copper ions. A strong dependence can be observed. The adherence has been evaluated using ultrasonic cavitation in water for thin film destruction.

Since the cathode of TVA is at earth potential and vacuum vessel also, it results that the plasma has a potential that accelerates the ions towards the vacuum vessel wall. This potential is roughly equal to the cathode potential fall (see Fig. 4).

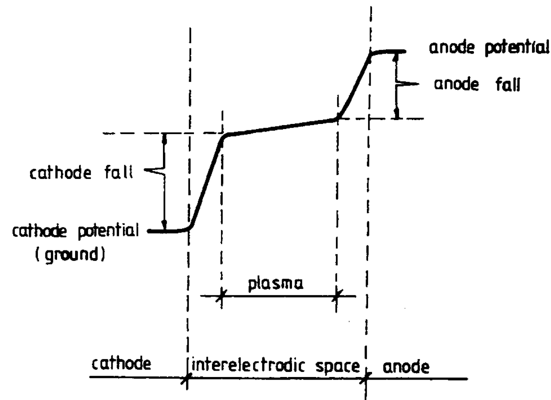

Fig. 4. Potential distribution in the cathode – anode space.

In these circumstances, besides the evaporated neutral atoms, on the sample are also incident energetic ions. So, the thin film is growing under the bombardment of ions of the material to be deposited. This is a major advantage in obtaining high purity thin films because the discharge is ignited in vacuum and the film is bombarded during its growing with own atoms which are ionized. We measured, using a special retarding potential analyzer, the energy of ions in a TVA discharge, an experimental curve being given as example in Fig. 5.

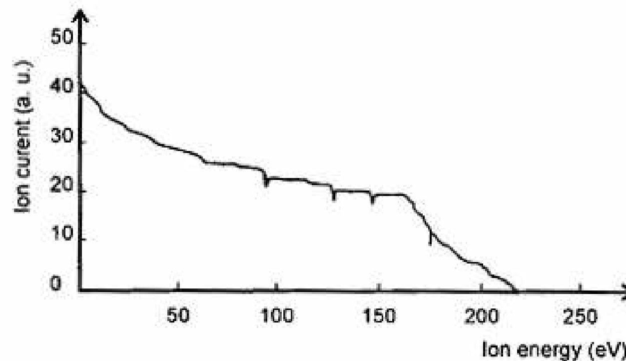

Fig. 5. Energy distribution of ions in TVA metal vapor plasma.

The ions have a random energy superposed on a much higher energy directed towards the wall. The directed energy of ions can achieve values of the order of 250 V. Our measurements on the potential distribution inside the vacuum vessel during TVA discharge have proved a continuous decrease of this potential from the value of the potential of the plasma source to the ground potential of the vacuum vessel wall. It results that the ion energy is directly related to the potential difference between vacuum vessel potential and plasma potential, i.e., cathode potential fall.

It results, that the ion energy of the TVA plasma can be straightforwardly controlled and established at needed value. For this, it is enough to control the cathode potential fall which in its turn is related to arc potential drop. We were able to establish the means to control the ion energy at a constant TVA arc current. A cathode fall increase is obtained using one of the below given changes of TVA parameters: (1) decrease of the cathode temperature, (2) increase of angle φ, (3) increase of the inter-electrode distance d.

An empirical relation can be established between the cathode potential fall and the TVA arc voltage drop, the relation between these two parameters being a linear one. In most of the cases, the ratio between these two potentials is roughly 1/2 - 1/3.

As mentioned in the recently published papers, the ion bombardment better ensures the quality of the deposited thin films. Due to the ion bombardment the thin films are compact, with no columnar structure and very smooth. The physical properties of the thin films are close to those of the bulk material.

We shall now underline our main obtained results in using TVA technology for thin film deposition: SEM analysis of the deposited thin films did not show droplets (droplets free deposition) and presented a compact structure of the fractured film.

Atomic force measurements of the deposited copper film have shown very smooth surfaces. Roughness values of the order of 40 Å were usual.

Also, we measured the roughness dependence on the value of the directed ion energy, thus proving a clear decrease of the roughness with the energy of incident ions on the depositing film (see Fig. 6).

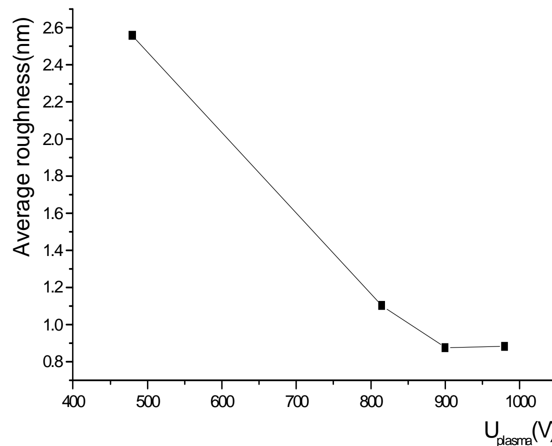

Fig. 6. Average roughness value dependence on arc voltage drop – i.e. directed energy of ions in the case of MgO layers.

Due to the incident energetic ions, the adherence of the thin film on the substrate increases especially in the case of plastic materials. In this case, in accordance with our results, the adherence increases with the value of the ion energy.

Recently, Thermionic Vacuum Arc has been used for carbon film deposition. The TVA technology is suitable for producing nanostructured materials because of the high power density of the vapour plasma generated by accelerated electron flux from the cathode and high energy of the ions incident on the depositing film, both these properties ensuring a high dispersion of the evaporated material. At condensation, the size of the generated structures will be in the range of nanometers.

Instead of a crucible, we used as anode a carbon rod with a diameter of 4-5 mm. Because during deposition the anode material is consumed, the carbon rod can be moved, keeping a constant distance between electrodes.

As sample support we used KCl and NaCl crystals in order to study the deposited thin film using TEM images.

The high-resolution TEM images show the beginning of the crystallographic ordering, with correlation lengths of about 15 Å. Within the correlation length are situated about 3-4 crystallographic planes. The distance between crystalline planes is 4 Å (3.9 – 4.1 Å), which corresponds to the (200) graphitic planes. The TEM resolution is 1.4 Å and the magnification is 1.4 M.

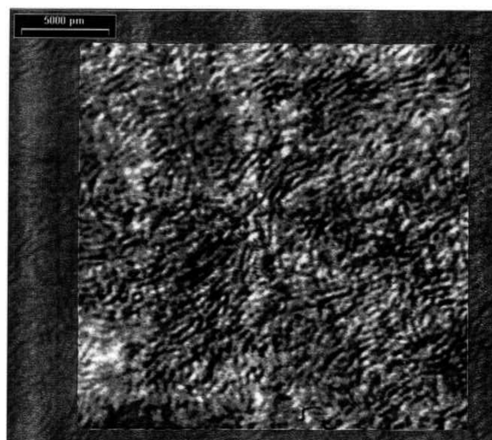

Fig. 7. The high resolution TEM image of the deposited carbon thin film.

4. Conclusions

The obtained results prove the advantages of the new deposition technology, namely Thermionic Vacuum Arc, which simultaneously provides low surface roughness, compact film structure, good adhesion, generation of nanostructured material, high purity films, which can be deposited also in high vacuum conditions. Moreover, the described new technology can be easily extended, without major difficulties.

References

[1] G. Musa, N. Betiu, I. Mustata, A. Baltog, A. Popescu, Rev. Roum. Phys. **28**, 907 (1983).
[2] G. Musa, A Baltog, A Popescu, N. Betiu, I Mustata , Contribution to Plasma Physics **27**, 431 (1987).
[3] G. Musa, E. Horst, The Physics of Ionised Gases, 18th SPIG, 195-210 (1997).
[4] G. Musa, H. Ehrich, J. Schumann, IEEE Transactions on plasma science **25** (1997).
[5] G. Musa, H Ehrich, A Popescu, I Mustata, A. Salabas, M. Cretu, G. F. Leu, Thin Solid Films **343**, 63 (1999).
[6] G. Musa, I. Mustata, A. Popescu, H. Ehrich, J. Schumann, Thin Solid Films **333**, 95 (1998).