Electrical contact resistance of tungsten coatings deposited on Cu and Al conductors

G Kotlarski¹,², S Valkov¹, A Andreeva³, V Mateev², I Marinova² and P Petrov¹

¹ Acad. Emil Djakov Institute of Electronics, Bulgarian Academy of Sciences, 72 Tsarigradsko Chaussee, 1784 Sofia, Bulgaria
² Technical University of Sofia, 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria
³ Faculty of Physics, St. Kliment Ohridski University of Sofia, 5 James Bourchier blvd., 1164 Sofia, Bulgaria

E-mail: pipetrov@ie.bas.bg

Abstract. In this work we study the effects of W coatings on the electrical contact resistance of Cu and Al conductors. The coatings were deposited by means of electron beam evaporation in a vacuum environment. The structure of the obtained samples was analysed using X-ray diffraction (XRD) and the surface roughness was studied by atomic force microscopy (AFM). The electrical contact resistance hysteresis of the W coatings and the base Al and Cu conductors is measured and analysed. The results obtained in this study are discussed concerning the possible applications of the coatings in the field of electrical engineering.

1. Introduction

Copper and aluminum are widely used materials in the field of electrical engineering. They have a vast majority of applications one of which is as electrical contact pads in circuit breakers, commutators, switches and other automated and semi-automated units used for switching circuits on and off, switching between circuits, for protection against occurring emergency situations, in induction motors, transformers and many more [1]. The reason that makes the aforementioned materials so attractive is their excellent thermal, mechanical and particularly electrical properties such as their high thermal conductivity and low electrical resistivity [2]. There are however some drawbacks related to poor corrosion and electrical erosion resistance [3, 4]. In an attempt to overcome those issues scientists all around the world have studied and found ways to combine copper and aluminum with other metals giving them the desired properties [5-7]. In our work we use an electron beam physical vapor deposition /PVD/ [8] to apply a tungsten coating on aluminum and copper samples. Tungsten is chosen due to its great thermal properties and corrosion resistance [9], which makes it ideal for increasing the electrical erosion resistance of electrical contacts. We characterize the effect of the coating on the electrical properties of Cu and Al by measuring their electrical contact resistance.

2. Experimental setup

For the purpose of our experiments, tungsten coatings are applied to the surface of pure copper and aluminum 2017 alloy samples using electron beam PVD. Before deposition of the coating, each sample is preheated to a set temperature – 250 °C and 450 °C. The parameters used during the electron beam deposition and the thicknesses of the applied coatings are summarized in Table 1. It is obvious
that in both cases the increase in the deposition temperature led to a decrease in the coating’s thickness. Under the conditions of higher substrate temperature during the deposition process, some amount of the deposited material was subsequent evaporated, which results in a significantly lower thickness of the coatings.

### Table 1. Parameters used during the electron beam deposition.

| Sample | Heating temperature, °C | Power of the electron beam, W | Deposition time, sec | Diameter of the electron beam, mm | Thickness of the coating, μm |
|--------|--------------------------|-------------------------------|----------------------|-----------------------------------|-----------------------------|
| Al 2017 | 250                      | 918                           | 90                   | 8                                 | 22                          |
| Al 2017 | 450                      | 918                           | 90                   | 8                                 | 6                           |
| Cu     | 250                      | 918                           | 90                   | 8                                 | 20                          |
| Cu     | 450                      | 918                           | 90                   | 8                                 | 5                           |

Each coating’s phase composition was studied by X-ray diffraction (XRD). The measurements were carried out within the range from 30° to 60° at 2θ scale.

In order to analyze the samples’ surface roughness we used atomic force microscopy (AFM). The received images have an area of 400 μm².

To evaluate the effect of the tungsten coating on the electrical conductivity of the copper and aluminum samples we measure their electrical contact resistance (ECR). In order to achieve the electrical contact between each set of samples they are places in a special unit, which can also be used to regulate the applied contact force. The samples are connected to a DC power supply current limited to 1 A. We measure the voltage drop in the contact zone using a millivoltmeter and use it to calculate the contact resistance via Ohm’s law. Since the power supply is current limited to 1 A, the measured voltage drop’s value in the contact zone is equivalent to that of the electrical contact resistance.

### 3. Results and discussion

Figure 1 presents the results obtained using X-ray diffraction (XRD). The patterns of coatings deposited on the Al substrate exhibit diffraction maxima of pure Al, α-W, which has the body-centered-cubic (bcc) crystal structure, as well as traces of WO₃ phases. Considering the diffractograms of the deposited coatings on Cu substrates, at a deposition temperature of 250°C peaks of pure copper, as well as a small amorphous-like halo is observable. This means that the deposited coating is amorphous. Considering the coating deposited at 450°C, besides the peaks of the Cu substrate, the β-W phase, which is an A:B solid with the A15 type crystal structure. The results obtained by the XRD measurement show that the W coating is in the form of different phase compositions, depending on the substrate. The films deposited on the Al substrate are in the form of α-W, while the phase composition of those applied on Cu consists of β-W. According to the authors of [10], the PVD deposited W coatings are in the form of β tungsten, and after annealing the films become in the form of α-W, which is in agreement with the results obtained in the present study. The difference in the thermophysical properties of the Al and Cu substrates plays a major role in the phase composition of the W films. It is known that the thermal conductivity of Al is much lower than that of Cu. Therefore, the cooling process of the specimens after the deposition occurs significantly faster in the case of Cu substrate – W film in comparison with the deposition of the same coatings on Al. Thus, the relatively lower cooling rate of the Al substrate plays a role in annealing of the coating.
Figure 1. XRD patterns of tungsten coatings deposited on: (a) aluminium substrate; (b) copper substrate.

There are a number of factors affecting the value of the electrical contact resistance. One of those factors is the surface roughness. The surface roughness of the obtained samples was studied using atomic force microscopy (AFM). The surface architectures of the coatings deposited on Al at 250°C and 450°C are shown in Figures 2a and 2b, respectively. Despite the seemingly more uniform nature of the surface roughness of the aluminum sample with a coating deposited at 450°C compared to that of the sample with a coating deposited at 250°C it has a higher average surface roughness (11.12 nm) compared to that of the samples preheated to a lower temperature (8.35 nm). That and the lower thickness of the coating observed at a higher temperature of heating are caused by the evaporation of part of the deposited coating. Due to the high surface temperature molecules of the applied coating separate from the surface of the sample and again turn into a vapor cloud. The same effect can be seen at the W coatings deposited on Cu substrates at different temperatures, namely 250°C and 450°C. The surface topographies of the specimens are shown in Figure 3. The measured mean roughness for the W coating deposited at 250°C was 37.6 nm, and increases significantly, to 54.9 nm for the W coating deposited at 450°C.

Figure 2. Surface area of aluminum samples with a tungsten coating deposited at: (a) 250 °C; (b) 450 °C.
Figure 3. Surface area of copper samples with a tungsten coating deposited at: (a) 250 °C; (b) 450 °C.

In order to study the effect of the tungsten coating on the electrical properties of the conductors we measure their electrical contact resistance. During the experiments, the applied contact force was changed. Figure 4 shows the relation between the electrical contact resistance and the contact force for Al and Cu samples with and without a layer of coating.

Figure 4. Relation of the electrical contact resistance and the contact force for non-coated, and tungsten coated (a) Al and (b) Cu samples.

As the contact force increases the contact resistance decreases. This is caused by the deformation of the contact pads which leads to an increasing of the contact surface area. A very common characteristic for the electrical contact resistance can be noticed during examination of the data for the Al samples. As the applied contact force increases, the contact resistance decreases to a certain point. Any subsequent increase of the contact force does not lead to a major decrease in the value of the electrical contact resistance. This means that the maximum deformation of the contact pads is reached. Any further increase of the contact force beyond the limit only leads to increasing of the influence of the fretting effect on the contact pads and may even lead to their complete destruction. Another common phenomena shown in the graph is the change in the values of the contact resistance as we decrease the contact force compared to the initial values during the increasing. That is again caused by the deformation of the pads. As the contract force increases, the contacts’ deformation increases thus the contact area increases. Once formed the new contact area decreases the electrical contact resistance permanently even after reduction of the contact force. The ECR of the aluminum samples is significantly greater than that of the copper ones due to the much higher electrical resistivity of Al and it’s more advanced stage of oxidation. Evidently the electrical contact resistance of the aluminum samples changes its’ value within the margin of error of the method of measurement indicating that the
applied coating does not affect the electrical parameters of the aluminum. Due to its’ thickness (22 μm) the coating applied at 250 °C has great mechanical properties and serves as a superb protective layer against corrosion and electric arcs. Since the coating applied at 450 °C is thinner (6 μm) it can only serve as a protective layer in non-commutating electrical connections where the mechanical forces applied to the coating are drawn to a minimum. The deposited coating significantly increases the ECR of the copper samples leading to higher loses in the contact zone. The coating’s adhesion with the base material is moderately poor which leads to a compromise in its integrity during commutation. The actual ECR of the copper contacts with a W coating is higher than that shown in the graph. Due to the degradation of its integrity with each commutation cycle the measurements taken during the experiment represent the mixture of the coating’s and the copper’s ECR. Considering the Cu samples, it is obvious that the resistivity increases significantly, where with an increase in the deposition temperature, the resistivity also increases. The can be attributed to the phase composition of the W coating which, at 450⁰ C, is in the form of beta phase, while the W coating deposited on Al substrate is in the form of alpha. According to the authors of [11], the resistivity of β-W is much higher than that of α-W. These results are completely in agreement with those obtained in the present study, where the increase in the Al coated samples is significantly lower in comparison with the Cu specimens.

4. Conclusions
Electron beam physical deposition is a viable method for applying protective coatings to improve the characteristics and lifespan of electrical conductors and electrical contact surfaces. In order to achieve an optimum quality coating the parameters of deposition should be very carefully selected. After processing the data from the conducted experiments, it can be concluded that better adhesion between the coating and the base material was achieved for the aluminum samples. The finished coating deposited at a temperature of 250 °C has a satisfactory mechanical resistivity which makes it ideal for use in commutating electrical devices for both high and low current applications. The coating deposited on the copper samples at both temperatures of preheating had poor mechanical resistivity, high electrical resistivity and could not sustain its integrity during the experiments. Further research needs to be conducted in order to apply a sufficient quality coating on the copper samples.

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References
[1] Sharma N, Khan Z and Siddiquee A 2017 Trans. Nonferrous Met. Soc. China 27 2113-2136
[2] Davis J 2001 Alloying: Understanding the basics (Materials Park, Ohio: ASM International)
[3] Salas B, Wiener M, Koytchev R, Badilla G, Irigoyen R, Beltran M, Nedev N, Alvarez M, Gonzalez N and Rull J 2013 ISRN Corrosion 2013 846405
[4] Wang Z, Jones G, Spencer J, Wang X and Rong M 2017 Sensors 17 519
[5] Larsson E, Andresson A and Rudolphi A 2017 Wear 376-377 634-642
[6] Kumar S, Parameshwaran R, Kumar S, Nathiya S and Heenalisha K 2020 Materials Today: Proceedings (Article in Press)
[7] Grieseler R, Camargo M, Hopfeld M, Schmidt U, Bund A and Schaaf P 2017 Surface and Coatings Technology 321 219-228
[8] Mattox D 2002 Metal Finishing 100 394-408
[9] Shabalin I 2014 Ultra-High Temperature Materials I Chapter 3 – Tungsten 237-315
[10] Hao Q, Chen W and Xiao G 2015 Applied Physics Letters 106 182403
[11] Vullers F and Spolenak R 2015 Thin Solid Films 577 26-34