Improving the quality of nanofilms produced by magnetron sputtering

V A Tupik¹, A A Potapov², V I Margolin¹ and D K Kostrin³

¹ Department of microelectronics and radio engineering, Saint Petersburg Electrotechnical University “LETI”, 197376, Saint Petersburg, Russia
² Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, 125009, Moscow, Russia
³ Department of electronic instruments and devices, Saint Petersburg Electrotechnical University “LETI”, 197376, Saint Petersburg, Russia

E-mail: V.Margolin@mail.ru

Abstract. Technological and structural aspects of the synthesis of nanoscale films by magnetron sputtering methods and ways for improving their uniformity and structural perfection are considered. Experimental results demonstrate that the proposed technological solution makes it possible to obtain high-quality coatings with almost complete absence of the droplet component.

1. Introduction

The production of thin films or coatings using modern technologies leads to the synthesis of new materials with improved characteristics and capabilities, which requires further development and application of new technological approaches. In the technological processes of deposition and synthesis of thin nanoscale films, the magnetron sputtering method is one of the most advanced and precise. It can be carried out both in the case of using a conventional sputtered cathode, and in the case of using an arc discharge.

In this case, the discharge characteristics change significantly, the discharge current increases sharply and the discharge voltage decreases. On the surface of the cathode, rapidly moving cathode spots appear, which are the centers of the discharge and realize the channels of current passage from the cathode to the anode in the form of dense plasma jets of the cathode material, forming a so-called plasma torch. Until now, there are no well-founded theoretical concepts and accurate experimental data on the processes in the cathode spot and the cathode arc torch, despite the abundance of serious research in this direction [1–5]. This leads to the need to apply various empirical concepts, which makes it necessary to rely mainly on experimental research.

2. Electric arc deposition of substances from a glow discharge plasma

Devices that use electric arc deposition of substances from an abnormal glow discharge plasma are popular and widely used. In their development and design, an outstanding role belongs to the Kharkov school of technologists, such as V M Shulaev, A A Andreev and a number of others [6–10]. The undeniable advantage of such coating devices is the higher adhesion of the substance sprayed on the substrate and the speed of coating process. There is an extremely high current density on the surface of
the arc evaporator, which causes local melting of the evaporator in the spot area. The molten metal vaporizes and passes through the combustion zone of the arc. In this case, the metal atoms are almost all ionized, accelerated by an electric field (the substrate is a negative electrode) and deposited with high energy, which ensures a high degree of adhesion of the applied coating.

But in all good things there is always something bad. In this case, it is the presence of a droplet phase in the plasma deposited stream, which is completely unacceptable for obtaining nanoscale films, since the size of the droplet, and, accordingly, the resulting island, will be several times greater than the thickness of the nanofilm. Therefore, an extremely important technological task is the exclusion of the droplet phase from the flow of the deposited material, which makes it possible to obtain films that are homogeneous in structure, including nanoscale films, the thickness of which is much smaller than the size of the droplet phase clusters.

3. Possible neutralization of the droplet phase
The advantage of such arc coating is a higher adhesion of the substance sprayed on the substrate. The molten metal vaporizes and passes through the combustion zone of the arc. In this case, the metal atoms are almost all ionized and the resulting ions, accelerated by the electric field, are deposited with high energy, which ensures a high degree of adhesion of the applied coating. However, the flow of ions falling on the molten metal creates pressure on the melt, which causes it to spray in the form of droplets up to 10 μm in size. In addition, local overheating of the working spot on the target and explosive evaporation are possible. These phenomena significantly increase the roughness parameter, which also makes it impossible to use them for applying nanoscale coatings in thickness.

In order to overcome these disadvantages, the standard magnetron arc sputtering device was equipped with an additional magnetron sputtering device, to which the substrate power supply was connected, and an additional AC power supply and an additional DC power supply were connected to the substrate holder. The operation of this device provides an increase in the uniformity of the obtained coatings and the achievement of high adhesion, but the droplet phase is not completely eliminated [11].

When coating substances, including metals and alloys, with a low melting point, arc ion cleaning is not carried out, the substrate holder is connected to an AC source and the parts are cleaned by an AC glow discharge, which, as practice has shown, is a more effective method compared to cleaning in a DC glow discharge plasma. In the case when the substrate holder is connected to a DC source, the coating will be sprayed with an additional magnetron device in the normal mode for it. The same mode can be used to produce metal mirrors with an increased light reflection coefficient, as well as for metallization of various dielectrics [11].

4. Complete exclusion of droplet phase clusters from the spray flow
To exclude the droplet phase from the sputtering process, the arc evaporator is equipped with a metal non-magnetic flap made in the form of a disk, the diameter of which is equal to the diameter of the cooled cathode. Structurally, this disk is located between the focus and stabilization coils coaxially with the cathode. In addition, inside the focusing coil there is an additional flap made of non-magnetic metal in the form of a truncated cone, the diameter of the larger base of which is equal to the inner diameter of the focusing coil, and the diameter of the smaller base facing the cathode is equal to twice the diameter of the flap [12].

To spray the material, the arc discharge ignition system uses a stabilization coil to generate an arc discharge on the cathode surface, which vaporizes the cathode material in the form of a stream of ions and a droplet phase. With the help of the focusing coil, a plasma torch is formed, directed along the axis of the system. The plasma torch contains both ions of the atomized substance and its droplets. The flap placed on the axis of the arc evaporator eliminates the flow of the sprayed substance from straight-flying droplets, and the flap installed inside the focusing coil from droplets flying at an angle from the cathode. It is made in the form of a truncated cone produce from a non-magnetic metal, and the diameter of the larger base of the cone is equal to the inner diameter of the focusing coil, and the
smaller diameter of the cone facing the cathode is equal to twice the diameter of the flap connected to the cathode of the arc evaporator [12].

The cathode material evaporates from the cathode spot, it passes through the plasma zone and is almost completely ionized, and the power of the arc discharge is such that ions “return” to the melt of the cathode spot. They put pressure on it and, as a result, lead to splashing of the melt. The resulting droplet phase clusters are electrically neutral and directed away from the cathode.

The ions drawn from the plasma form a torch with the maximum current density distribution along the axis of the system under consideration. Droplets of the molten metal fly out in all directions.

Since the flap in the form of a disk is not connected to any element of the arc evaporator, the ions falling on it from the cathode will charge it. The charge of the flap will increase until the electric field formed by it completely repels the ions, which will go around the flap and move along the same trajectory, rotating around the magnetic force lines of the coils.

The condensed phase products of evaporation, moving along the axis of the arc evaporator are limited by the damper, located on the axis of the system, since the droplets are not charged, and the diameter of the valve is equal to the diameter of the cathode, that part of the droplets that is sprayed at an angle is blocked by the damper in the form of a truncated cone, fitted close to the focus coil. The inclination of the cone towards the cathode prevents small droplets from “reflecting” from it and removes them from the deposition flow.

Due to the fact that the flap in the form of a disk is charged, the ion torch will flow around it and the ions will move in a straight direction, unlike the droplet phase. The diameter of the disc flap must match the diameter of the cathode to isolate the coaxial drip flow. If it is smaller, then some of the drops will “break” in the forward direction. If it is larger, it will reduce the flow of ions around the flap [13].

As an experimental test, the deposition of copper films on a dielectric substrate was carried out both according to the standard method (figure 1) and in the case of using a flap (figure 2). In figure 1, teardrop-shaped formations in the form of copper hills were found, which are the frozen condensed copper droplets. The sample was examined by scanning electron microscopy. Figure 2 shows the effect of applying a coaxial damper that prevents the passage of the droplet phase to the substrate. Condensed droplets were not detected using either a scanning electron microscope or a more precise atomic force microscope.

![Figure 1. Copper droplet formations on the substrate. Scanning electron microscopy.](image1)

![Figure 2. Condensed film without droplet phase. Atomic force microscopy.](image2)

5. Conclusions
As the experiments show, the smaller diameter of the cone should ensure the isolation of the droplet phase and the passage of the plasma torch. At the same time, it is sufficient that its diameter is equal to twice the diameter of the flap connected to the cathode of the arc evaporator.
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