Obtaining thin metal films and their compounds using magnetron sputtering and arc evaporation in a single technological cycle

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Abstract. The authors of the article consider the possibility of obtaining thin films using magnetron sputtering and arc evaporation. The prospects of combining these methods in a single processing unit for obtaining films with high performance characteristics have been shown.

Thin films of various materials have found wide application in many fields of science and technology. First of all, these are conductive, semiconductor, dielectric, protective and other layers in microelectronics, wear-resistant coatings on tools and protective and decorative coatings on machine parts and on industrial and household products. The thin film properties depend upon not only the material, but also to some extent upon its crystallographic structure.

The most advanced layers are grown using chemical vapor deposition from the gaseous (vapor) phase (CVD). In this case, film growth occurs through the successive deposition of layers, i.e. tangential movement of the steps. This method has many limitations. In the first place, it is the presence of an alignment substrate and a high temperature of the growing process.

Physical vapor deposition methods for thin films obtaining do not have those limitations. These methods are characterized by non-equilibrium crystallization conditions. When non-alignment (amorphous and polycrystalline) substrates are used, film growth occurs according to the standard process. The predominant film growth direction depends on the atomic structure of the material being grown and the alignment of the films relative to the substrate is dependent upon the direction of the film-forming particles flow [1]. Joining of new particles to the atomically rough (diffuse) surfaces takes place from the macroscopic point of view in any spot, so that the surface in the process of growth shifts along the normal line to itself at each point [2]. Films grown using these methods have a fibrous (columnar) structure (figure 1). Texturing of fibers for materials with a cubic lattice (TiN, ZrN, etc.) is possible along the <111> directions, less often <100>, <110> directions, and in binary diamond-like compounds with a wurtzite structure (AlN, ZnO, etc.) in <0001> direction, and less often in <1120> one.

Figure 1 is the photograph of AlN film chipping showing the structure of the film. The space between the fibers is filled with an amorphous phase. Impurity metal atoms can be spread in the form of point defects, both in the crystalline phase and in the amorphous one. When the concentration of impurity atoms is higher than 5% and when the drop phase is on the substrate, the amorphous metal clusters are formed at the interfaces [3].
Thus, to obtain thin films with the required properties, a bond between the growth conditions and the crystalline structure should be established. In this case, finding the crystallographic grain orientation in the film is far from being sufficient. It is also necessary to evaluate the degree of crystallinity, i.e. the ratio of the crystalline and amorphous phase.

Among the physical vapor deposition methods, magnetron sputtering and arc evaporation are the most widely used ones.

The electric discharge arising in the working chamber, vacuum-treated to the pressure of $10^{-4}$ Pa and below, belongs to the class of so-called vacuum arcs or high-current discharges burning in vapors of the cathode material, i.e. the so-called cathode form of a vacuum arc with integral cold electrodes and an eroding cathode is executed. The discharge at the anode with a developed surface (the body of the working chamber) is diffuse. The discharge at the cathode exists in the form of the cathode spots.

The local energy density in the cathode microspots, chaotically moving along the integrally cold cathode surface is rather high ($10^6–10^7$ W/cm$^2$). This causes a high erosion rate (evaporation) of the cathode material in the area of cathode microspots. Erosion products of the cathode material are emitted from the area of cathode microspots in the form of high-speed plasma jets with a high ionization degree (up to 80%).

A flow of the deposited substance is formed as a plasma flow with a high ionization degree and high particle energy. This flow condenses on the surface of the substrate, forming a film. Ion bombardment of the growing film strongly affects the microstructure and the structure of the crystalline phase.

Ion bombardment of the substrate is especially important for growing films using reactive sputtering. These are, first of all, films of metal nitrides, oxides and carbides with high hardness, wear resistance and thermal conductivity. Films are obtained by adding a reaction gas into the working chamber, which results in the fast chemical direct synthesis reaction on the substrate surface when the active plasma of the cathode material and the gas (oxygen or nitrogen) added into the chamber are mixed.

The downside of arc evaporation is the presence of a droplet phase in the film resulting in the deterioration in the continuity and corrosion characteristics of the coating. A highly ionized flow of a high density of deposited particles onto a substrate being under bias voltage induces high internal stresses in the film. Therefore, to obtain good adhesion of the coating on some substrates, high-quality cleaning of the substrate (including ionic one) is required. It is also necessary to keep a high temperature of the substrate during the deposition process. When using low-temperature materials as a substrate, for example, tools made of high-speed steel, a high temperature in the condensation zone results in the dull surface and the edge of the tool is tempered. It is especially pronounced during heating and ionic cleaning of the tool surface in the arc discharge plasma when high (> 1 kV) voltage is applied to the substrate.
Magneton sputtering (one of the methods of ion sputtering, which is primarily features the presence of a magnetic field at the sputtered surface of the target, which supports to localize the plasma and thereby to increase the sputtering rate) using a standard magnetron (SM) does not have these disadvantages. The content of the amorphous phase in the film is rather high because this method has a low degree of deposited particles ionization.

The development of magnetron sputtering methods, the emergence of unbalanced magnetrons (UM) made it possible to expand significantly magnetron sputtering application. Due to the special configuration of the UM magnetic field, ionization of the working gas and sputtered particles occurs not only at the target surface, but also throughout the entire length from the target to the substrate, i.e. the film is growing under ion bombardment. The degree of ionization of the sputtered particles is 1–10% [4].

At the same time, to implement this method high pump rates and more precise process conditions of growing metal nitride, oxide and carbide films are required. In addition, it easier to coat parts of complex geometric shapes at a large target-to-substrate distance using arc evaporation.

Table 1 shows the comparative characteristics of arc evaporation (AE) and magnetron sputtering (standard magnetron - SM, unbalanced magnetron - UM).

| Parameter                                      | AE    | SM    | UM    |
|------------------------------------------------|-------|-------|-------|
| Emission energy of the material, keV/atom      | 0.25  | 1     | 1     |
| Ionization of metal particles, %                | 80    | 10    | 10    |
| Power loss at the cathode, %                    | 30    | 90    | 90    |
| Target-substrate distance d_{s-t}, mm           | 200–400 | 40–80 | 50–200 |
| The current density on the substrate at d_{s-t} = 50 mm, mA/cm² | 150 | 0.5  | 0.5–10 |
| The current density on the substrate at d_{s-t} = 200 mm, mA/cm² | 10  | 0.1  | 0.1–5  |
| Ion / atom ratio                                | 1.5   | 0.4   | 0.3–15 |
| at d_{s-t}, mm                                  | 300   | 50    | 200   |
| Critical pump speed, l/s                        | 50    | 250   | 250   |
| Presence of a droplet phase                     | yes   | no    | no    |
| Coating of complex shapes                       | easily | hard  | yes   |

The combination of both methods in a single processing unit allows us to obtain thin films of various materials with the required characteristics. With this purpose in mind, the arc evaporation unit NNV6.6 I4 was redesigned. We additionally installed 4 unbalanced magnetrons with a target size of 85 x 500 mm (figure 2).

The standard technological process, for example, to make protective and decorative coatings, can consist of the following steps:

1. Loading items into the working chamber.
2. Obtaining vacuum and heating items using a resistive heater.
3. Cleaning items in a glow discharge.
4. Cleaning items in a magnetron discharge, a high voltage being applied to the substrate.
5. Deposition of a transition temperature-protective and corrosion-resistant titanium layer using magnetron sputtering.

Table 1. Typical parameters of various coating methods.
6. Deposition of a wear-resistant, decorative layer of titanium nitride or zirconium nitride using arc evaporation.

![Image](image_url)

**Figure 2.** Photograph of the redesigned unit NNV6.6 I4.

The redesigned unit with a slight change in the technological process supports to apply various types of thin films on the substrates with the desired crystal structure.

Thus, the combination of arc evaporation and magnetron sputtering in one technological unit significantly expands the range of materials used and improves the quality of the coatings obtained.

**References**

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