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Original
Review of methods for producing nanocoatings in vacuum / Saidakhmedova, G., Saydakhmedov, R., Inoyatkhodjaev, J., Maizza, G.. - In: ACTA PERIODICA TECHNOLOGICA. - ISSN 2406-095X. - 56:(2025), pp. 359-375. [10.2298/apt250617025s]

Availability:
This version is available at: 11583/3008094 since: 2026-03-03T11:17:37Z

Publisher:
University of Novi Sad, Faculty of Technology

Published
DOI:10.2298/apt250617025s

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26 November 2026

Acta Periodica Technologica
BIBLID: 1450-7188 (2025) 56, 1-491
APTEFF, 56, 359-375 (2025)
https://doi.org/10.2298/APT250617025S
Review paper
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REVIEW OF METHODS FOR PRODUCING NANOCOATINGS IN VACUUM

Gulirano SAIDAKHMEDOVA[1], Ravshan SAYDAKHMEDOV[2], Jamshid INOYATKHODJAEV[3], Giovanni MAIZZA[4]*

[1] Turin Polytechnic University in Tashkent, Olmazar district, Kichik Halka street 17, Tashkent, Uzbekistan.
[2] Tashkent State Transport University, Aviation Engineering Department. Mirabad district, Temiryulchilar street 1, Tashkent, Uzbekistan.
[3] Inha University in Tashkent. M.Ulugbek district, Ziyolilar street 9, Tashkent, Uzbekistan.
[4] Politecnico di Torino, Department of Applied Science and Technology, Turin, Italy.

Received: June 17th, 2025. **Revised: 20th, 2025.** **Accepted: 25th, 2025.**

This article describes the role of functional coatings in the industry and methods of applying coatings to components and tools, in order to increase the durability of parts and also improve wear resistivity. Today, functional coatings have a wide range of applications. Furthermore, the methods of deposition of materials by different methods effect on various properties of substrate. The most uniform surface is achieved by using vacuum deposition at low pressure. The advantages of physical deposition are high degree of resistance to wear, corrosion and adhesion. The advantages, disadvantages and features of obtaining various functional nanocoatings have considered. Furthermore, given the sputtering devices of magnetron, ion-plasma with cathodes and ion-beam methods. The most effective ion deposition devices are vacuum-arc evaporators with cooled cathodes.

Keywords: Physical vapor deposition, Thin films, Arc sputtering, Magnetron sputtering, Ion-plasma deposition, Evaporation

INTRODUCTION

Protecting machine parts, mechanisms and metal structures from wear and corrosion, increasing the reliability, quality and durability of equipment, and creating competitive products are among the most important tasks of industrial policy.

It is known that about 20% of the annual metal smelting in developed industrial countries is spent on replenishing the costs of wear and corrosion. For example, against wear in most cases is based on the traditional design of parts from bulk alloyed materials with subsequent heat treatment, well-known methods of chemical-thermal treatment or the application of electrochemical coatings. Currently, this approach is complicated by the scarcity and reduction in the range of materials of manufactured metal products, their excessively high cost, high energy consumption for thermal or chemical-thermal treatment, and environmental problems associated with galvanic production. In addition, increased requirements are constantly being put forward for reliability, durability, competitiveness of products, new operating conditions for machines and mechanisms, which fundamentally cannot be satisfied when using any one complex alloy. In this regard, it is technically advisable to use parts and products whose surface properties are radically different from the properties of the material core through the use of various modern coatings and surface hardening methods.

Physical deposition (PVD) and chemical deposition (CVD) methods are known. Physical methods of deposition of coatings in a vacuum are more attractive. These include me-

* Corresponding author: Gulirano SAIDAKHMEDOVA, e-mail: saidahmedovagulirano@gmail.com

thods such as electron beam evaporation, ion plasma sputtering, magnetron sputtering, vacuum arc evaporation.

ION-PLASMA DEPOSITION OF COATINGS

Technologies for surface treatment of various materials under reduced pressure (in vacuum) are currently a well-developed field of science and technology. Methods associated with the formation of various functional coatings and modified areas on the surface of materials have been sufficiently studied and are successfully used in practice (1-5).

Many of the methods of vacuum deposition of materials, plasma and ion treatments or their modernized versions can be considered as nanotechnology methods. These methods make it possible to create nano-sized or nanostructured coatings on the surface of materials, multilayer and composite materials with nanocomponents.

Vacuum methods can be divided into technologies based on physical (thermal and ionic) processes and chemical (plasma-chemical) processes for processing materials.

Among all nanotechnologies for surface treatment, ion-vacuum technologies for producing thin coatings (PVD and CVD technologies) are quite promising. Coatings formed by such methods are characterized by high adhesion, while the temperature effect on the base material is relatively small. Analysis of literature data showed that the crystallite size in coatings obtained using vacuum deposition technologies can reach 1-10 nm. The thickness of the formed coatings and modified surface areas ranges from 1-2 nm to hundreds of nm and is determined by the coating deposition modes and subsequent treatments (6,7).

DEVICES FOR THERMAL AND RADIATION EVAPORATION OF MATERIALS

PVD (Physical Vapor Deposition) methods have a generally similar coating scheme using low pressure (Figure 1).

In this case, the working material is transferred to a state of steam, in the working chamber it is transferred to the substrate (base), were deposition of coating material. The use of vacuum greatly facilitates the transfer of the material into the vapor phase and its transfer to the base.

Vacuum deposition methods differ in the methods of evaporation, transportation and modes of coating formation. The widespread use of environmentally friendly PVD methods is due to the possibility of obtaining uniform coatings with a thickness of 1-2 nm to tens of microns with good reproducibility.

The size of the processed surface is usually limited by the vacuum working chamber, but in some cases, it is possible to process long strips (roll materials) of almost unlimited length. It is possible to selectively apply coatings to selected areas and have an almost unlimited choice of substrate materials. It is possible to obtain multilayer coatings with layers of different thicknesses from different materials; it is possible to change the composition, structure and properties of coatings by changing deposition parameters.

The disadvantages of this group of methods include: the relative complexity and high cost of technological vacuum equipment, the complexity of developing technological modes for some cases of coating formation. In particular, for obtaining coatings from complex compounds while maintaining high precision of the chemical composition, the difficulty of forming coatings of large thickness and obtaining coatings inside cavities and tubes of small diameter.

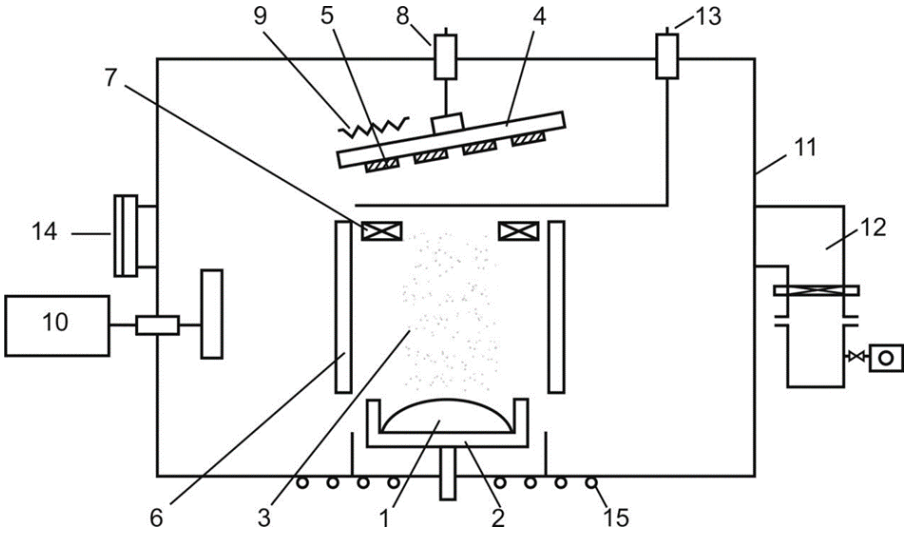


Figure 1. Typical setup for PVD coating.

1 - coating material, 2 - system for transferring the material into the vapor phase, 3 - flow of evaporating material, 4 - substrate, 5 - coating being formed, 6 - system for transporting the coating material in the vapor phase to the substrate, 7 - system for focusing or scanning the flow of matter , deposited on the substrate, 8- system for fixing the substrate and its controlled movement, 9- system for regulating the temperature of the substrate, 10- system for controlling and monitoring technological parameters (substrate temperature, material deposition rate, pressure in the chamber, coating thickness), 11- vacuum operating camera, 12 - system for creating and maintaining high vacuum (system of vacuum seals, fore-vacuum and high-vacuum pumps, nitrogen trap), 13 - damper for interrupting the flow of vapors, 14 - inspection windows in the chamber, 15 - cooling system for the working chamber and individual units of the installation.

The most common method is vacuum deposition of coatings by thermal evaporation of various materials, in particular metals, at pressures of $10^{-1}\div10^{-7}$ Pa. The deposition process includes creating the required initial degree of vacuum, heating the evaporated working material until steam forms at a pressure of 0.1^{-10} Pa in the heating zone, and deposition of vapor on the substrate being processed in the selected mode. Temperatures at which effective evaporation of most metals occurs are 1000-1800 K.

The thermal evaporation method can be used to obtain coatings of many non-degradable materials, but significant difficulties are caused by the evaporation of refractory materials, alloys and compounds, the composition of which changes when heated, as well as interaction with the evaporator. Coating deposition rates during thermal evaporation are usually 0.1÷100 nm/s. The thickness of the coatings is determined by the physical and technological parameters of the evaporation process and the distance from the evaporator to the substrate being processed. As a rule, the thickness of the coatings is proportional to the volume of the sample being completely evaporated and inversely proportional to the square of the distance from the evaporator to the substrate (8-11).

To heat and evaporate materials in a vacuum, the heat generated in directly heated resistive evaporators made of refractory materials (W, Mo, Ta, TiB_2, C) and boats of various shapes is most often used. In directly heated evaporators, filament currents reach hundreds and thousands of amperes. So, to heat tungsten or tantalum evaporators with a cross section of 1 mm^2 to 1000-2000 K in a vacuum due to Joule heat, currents of 50-100 A are required.

The Figure 2 shows some evaporators of working materials (crucibles and boats) made of refractory metals and compounds (W, Mo, Ta, C, TiB2). Moreover, worth mentioning is the method of explosive evaporation of materials, based on the release of a large amount of energy in a short period of time. In this case, the material evaporates and then, due to a rapid increase in volume, it cools with condensation of vapors into small particles.



Figure 2. Various types of evaporators made of refractory materials

Sometimes part of the material may not have time to evaporate, melts and separates into droplets. To supply the required amount of energy, a powerful pulse of electric current, an arc discharge or a laser pulse are used.

The most widely used technology option is the explosion of a wire with a diameter of 0.1-1 mm under the influence of a current pulse with a duration of 10^{-5}-10^{-6} s, a voltage of up to several kV and a current density of 104-106 A/mm^2. The diagram for obtaining powder from wire by explosive evaporation is shown in Figure 3.

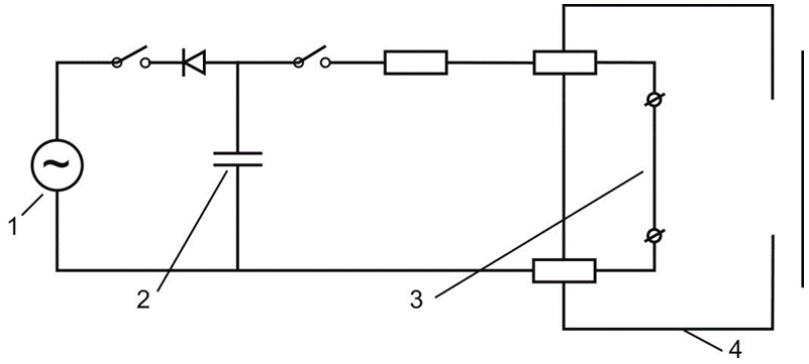


Figure 3. Scheme of wire evaporation by explosive method.
1 - voltage generator in the charging circuit, 2 - special capacitor, 3 - exploding replacement wire, 4 - chamber with inert gas.

To apply coatings, including nano coatings, the method of electron beam evaporation of materials with a focused beam with an energy of 5÷50 keV of various powers can be used.

Figure 4 shows schematic illustration of the angular electron-beam evaporation technique.

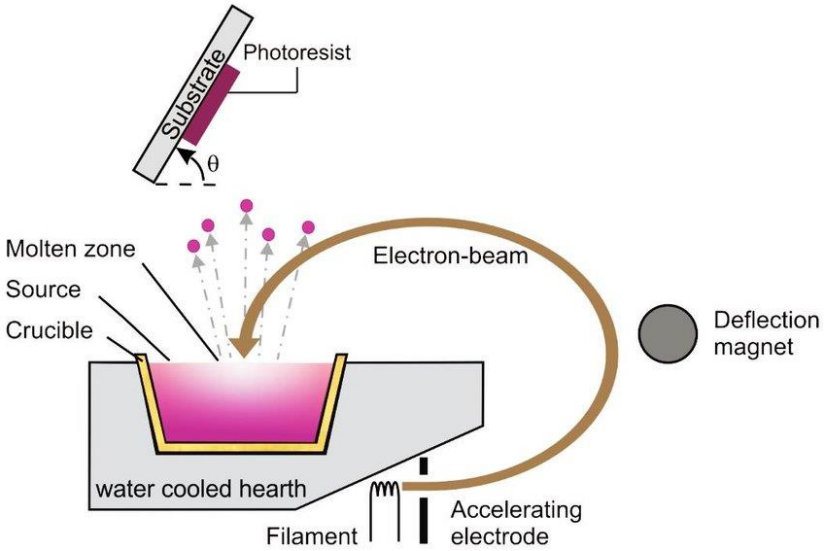


Figure 4. Schematic illustration of the angular electron-beam evaporation technique

The disadvantages of the electron beam evaporation method are the complexity of the design and power supplies, the difficulty of evaporating a material consisting of substances with different vapor pressures at the same temperature (it is problematic to obtain multi-component coatings with a given chemical composition), and high process temperatures (12-15).

DEVICES FOR ION AND ION-PLASMA SPUTTERING OF MATERIALS

For applying coatings of refractory materials (Mo, W, Ta) and materials with an evaporation temperature of more than 2300 K, as well as complex alloys, such as copper (brass) and resistive (RS) and compounds, such as oxides and nitrides (for example, SiO_2, ZrO_2 TiN), it is necessary to use other methods of vacuum coating, in particular various options for cathode sputtering of working materials in combination with ion treatment of the substrate surface.

It is known that bombardment (treatment) of the surface of solids with ions with sufficiently high energy is accompanied, first of all, by sputtering (emission) of the processed materials into a vacuum (sputtering of the target). Cathode sputtering (sputtering by ion bombardment) is historically associated with the destruction of cathodes in gas-discharge devices, has been studied since the beginning of the last century, and the main principles of this process are now well known (16, 17).

The pulse mechanism of destruction of the surface of solids during ion bombardment in a vacuum is generally accepted. When accelerated ions interact with atoms of a solid, momentum is exchanged between the ion, the lattice atom, and the lattice atoms among themselves. Assuming pair elastic collisions of these particles, it is possible to calculate all significant parameters of their elastic scattering - scattering angles, transferred energy.

To remove atoms from the surface, they must be given an energy that exceeds the binding energy of the atoms with the surface of the body. When ions collide with atoms of a solid, a cascade of displacements occurs, with a number of scattered atoms producing pulses directed towards the surface, which leads to cascading motion of atoms and, ultimately, sputtering. Calculated and experimental values of the threshold sputtering energy for a wide variety of materials (Al, Si, Ti, Cr, Cu, Nb, W, Au and others) are 13-40 eV. The sputtering itself is characterized by a statistical value, the sputtering coefficient S (atom/ion), determined by the ratio of the number of "knocked out" atoms to the number of ions bombarding the material.

The simplest version of the cathode sputtering method is a two-electrode one, which is based on the use of glow discharge plasma in a vacuum at a pressure of the order of 10-0.1 Pa. Before starting the process, in order to remove residual gases, a vacuum degree of 10^{-2}-10^{-3} Pa is usually created in the vacuum working chamber, after which an inert gas is supplied into the chamber (usually argon is used). A constant voltage of 1-5 kV is applied between the cathode (target made of sputtered material) and the anode (usually the body or substrate on which the coating is applied). This voltage value exceeds the ionization potential and breakdown voltage, so a sufficient number of secondary electrons are emitted from the cathode, which ionize the working gas.

To increase the productivity of the process and improve the vacuum conditions of sputtering, more complex schemes are used, including the multi-electrode method of cathode sputtering. With a multielectrode circuit using additional discharge sources. The discharge voltage can be adjusted in the range from -0.5 to -10 kV, and the discharge current to the target reaches 1 A, independently of each other.

The discharge occurs due to the potential difference between the filament cathodes and the anode, and sputtering occurs when gas ions collide with the target cathode. This makes it possible to significantly facilitate the formation of plasma and the process is carried out at a higher vacuum (0.1 Pa), and therefore ensures better purity of the deposited material (18).

Ion-plasma sputtering of working materials (cooled cathodes) with ion treatment of the substrates was carried out in a device containing discharge chamber, cathode unit, two plasma sources, sample container and power supplies.

The cylindrical discharge chamber made of stainless steel had water-cooled walls due to soldered tubes and a flange for connecting to the vacuum chamber, 2 flanges for plasma sources and an opening flange on which the cathode unit was attached. The cathode unit was a water-cooled copper disk Ø 180 mm with an insulated input. A sprayed material (Ta, Mo, Ti, Ni-Cr) with a thickness of 0.5-2 mm was attached to the front surface of the disk.

On the side flanges with a diameter of 100 mm, two plasma sources were located, which were a cylindrical cooled anode with a diameter of 60 mm, inside which a W cathode with a diameter of 1.5 mm was inserted. The insulated cathode leads were water-cooled in the area of contact with the wires. On permanent magnets (magnetic system) were installed on the outer part of the flanges, providing an induction in the cathode zone of 0.03 T. A working gas leak (Ar, O_2, N_2) and a gas supply line were connected to the discharge chamber. At the output part of the device there was a rotating container with 8-10 planes with the surface heated by an IR lamp. The ion-plasma sputtering device is shown schematically in Figure 5.

The sputtered cathode power supply includes autotransformers, a step-up three-phase transformer up to 5 kVA and a rectifier. The unit provides adjustable negative voltage (from 100 V to 5 kV) at load currents up to 500 mA, and overload protection. The power supply of the plasma sources included a step-down filament current transformer (up to 150

A), a step-down transformer and a rectifier providing an anode voltage from 20 to 100 V at load currents up to 50 A. The substrate holder power supply made it possible to apply an adjustable negative voltage to the samples up to 1000 V at load currents up to 300 mA.

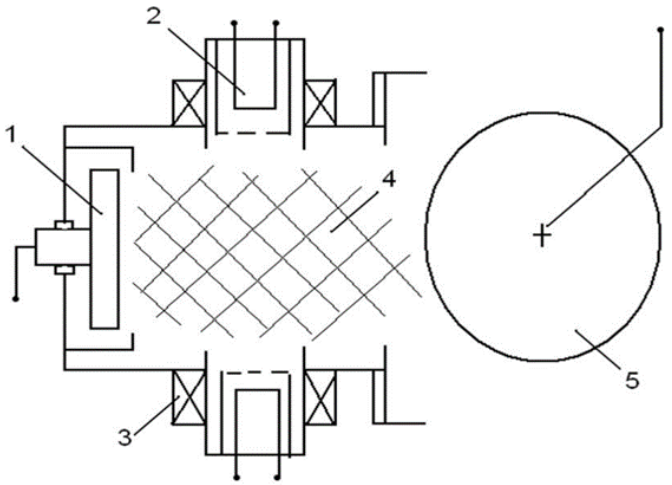


Figure 5. Ion-plasma sputtering device with thermal cathodes.
1-cooled target, 2-hot cathode and cooled anode, 3-electromagnetic coil, 4-plasma zone, 5-container with samples

A relatively effective device for deposition of thin coatings in a vacuum using sputtering of materials in crossed electric and magnetic fields is a magnetron sputtering source with a cooled cathode. The device allows you to spray non-magnetic materials and alloys (19-30). To increase the productivity of the process, a magnetic field is applied to the cathode discharge area, which concentrates the plasma on the cathode target. The trajectories of electron motion are located between the entry and exit points of the magnetic field lines; it is in these places that the intense formation of plasma and the occurrence of sputtering processes are localized.

Figure 6 shows a general diagram of a device for magnetron sputtering of materials and the design of one of the variants of a magnetron with a disk water-cooled cathode.

A magnetron sputtering device of various sizes was mounted on a separate stainless-steel flange with a thickness of 10-15 mm and included the following main parts: a cooled cathode, a magnetic system, vacuum inputs, a gas supply line, a damper, a substrate holder, and power supplies. A flange with a rubber seal was connected to the vacuum working chamber; the sputtered cathode made of materials (Al, Al-Si, Cu, Cu-Zn, Cr, Ni-Cr, Ti, Zr, Mo, Ta, Zn and alloys) had the shape of a disk with a diameter 80-160 mm thickness 4-10 mm.

The cathode is secured with non-magnetic ties or screws to a magnetic system, which is a single permanent magnet or a set of magnets made of a special alloy with a steel magnetic core. The assembled magnetic system provided a magnetic field induction of 0.05-0.10 Tesla in a gap of 15÷25 mm between the poles.

The system was connected by two inputs with a diameter of 8-10 mm made of stainless steel, having fluoroplastic or ceramic insulators with seals.

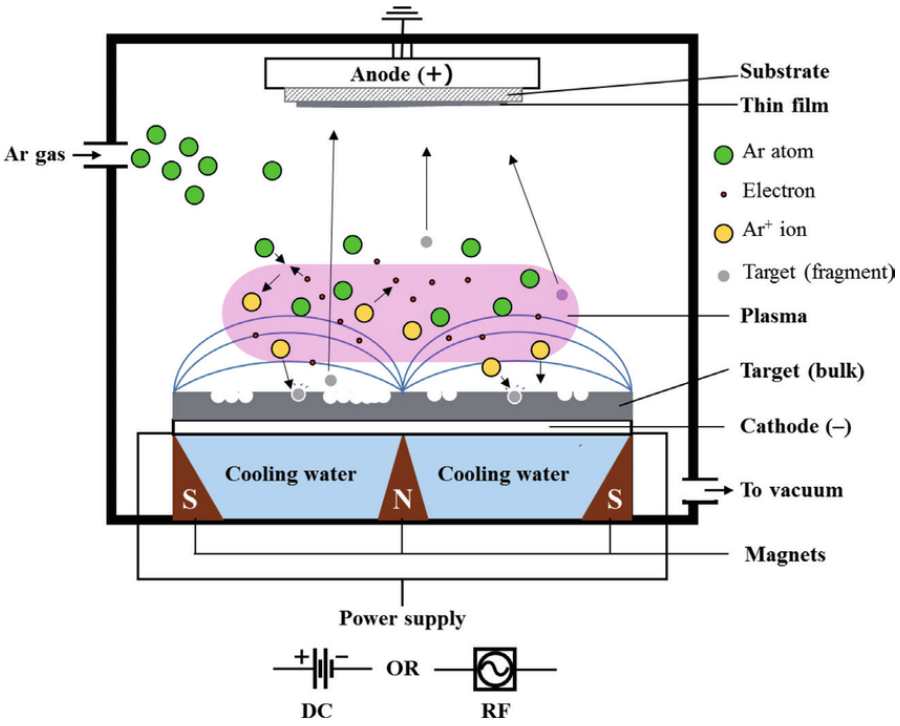


Figure 6. Magnetron sputtering diagram

A replaceable cylindrical stainless-steel anode is installed around the cathode at a distance of no more than 5-8 mm. A titanium rotating valve is installed above the magnetron cathode. The damper consisted of two layers (insulator and metal), while the outer disk was connected to a rotating device and connected to an electrical (up to +5 kV) input into the vacuum. The power supply of the magnetron material sputtering system must provide a relatively high initial voltage when the discharge is ignited, a stable discharge current at operating voltages of 300÷700 V, protection against current overloads (with microarc discharges) without interrupting operation, and protection against short circuits. To power the magnetron, a BP-196 unit can be used, providing a discharge current of up to 4.5÷5.0 A at 300-600 V and an initial open-circuit voltage of about 1000 V.

It should be noted that at the initial moment, increased voltages at the cathode are required to ignite the discharge. As a rule, the formation of microarc discharges along the cathode surface is observed, which disappear after cleaning (spraying a thin layer) of the surface (31-37). The presence of electrodes near the cathode (closer than 20 mm) leads to discharge failure or an increase in operating voltages by 1.5–2 times. The minimum pressure at which a discharge is observed is $8 \cdot 10^{-2}$ Pa, the optimal working gas pressure, as a rule, is in the range from $1.2 \cdot 10^{-1} \div 1.7 \cdot 10^{-1}$ Pa.

Figure 7 shows photographs of a number of developed devices for magnetron sputtering of materials with a disk cathode. The deposition of materials by magnetron sputtering, as well as cathode sputtering, allows the formation of coatings from metals and alloys. The thickness of the coatings is determined by the cathode material, sputtering mode (discharge current), distance to the substrate and a number of other factors.



Figure 7. Photos of magnetron sputtering devices with a disk cooled cathode

There are also options for vacuum ion-beam sputtering of materials (sputtering of materials with a high-energy ion flow), which are actually improved versions of cathode sputtering methods (Fig. 8). In this case, flows of inert gas ions move towards the sputtered material (target) from a separately located independent ion source in the form of a concentrated flow with an energy of 1-10 keV. Since the formation of an ion flow is not associated with the sputtered material, sputtering of any materials is possible (for dielectrics when using a device that compensates for the accumulation of potential on the target surface).

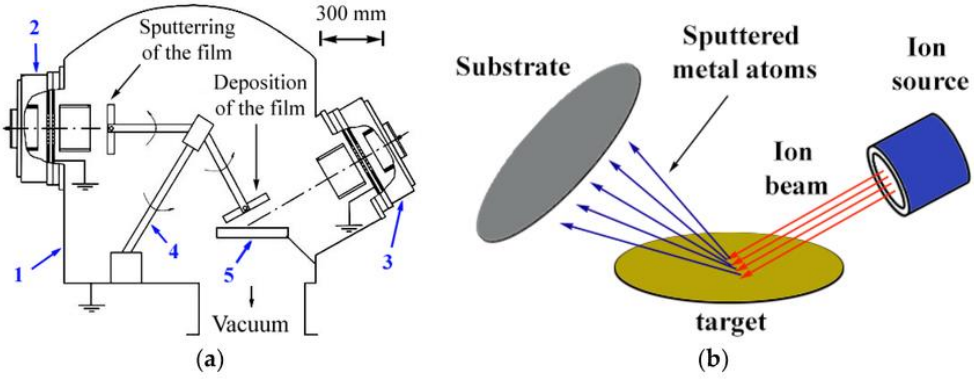


Figure 8. Diagram of the device for ion-beam sputtering of materials
Ion-beam sputtering–deposition unit (a) and the process of ion-beam deposition (b). 1. vacuum chamber; 2. and 3. ion sources for sputtering and deposition of the film; 4. substrate rotation mechanism; and 5. target.

For ion-assisted deposition of nanocoating, cold cathode ion sources can be used in combination with coating deposition. This makes it possible to reproducibly treat the surface of targets with a flow of ions with a given energy in the area of combining the zones of ion exposure and deposition. The device may consist of a separate magnetron sputtering source and an ion source located at an angle to each other, or two ion sources (38). The design of one of the options for an ion source with a cold cathode is shown schematically in Figure 9.

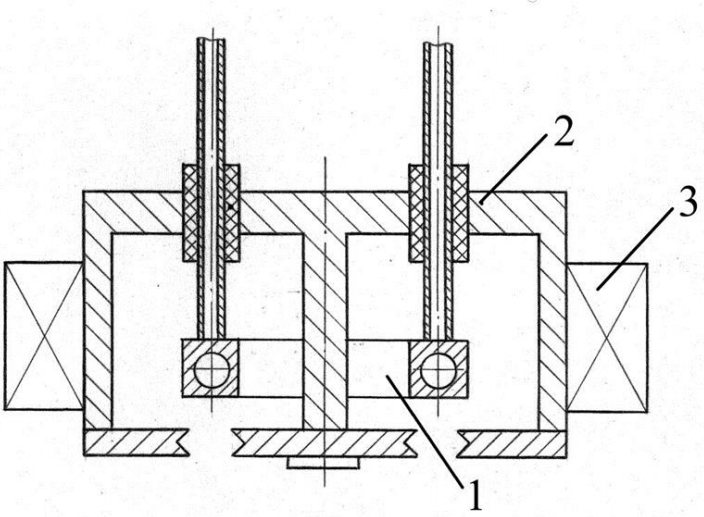


Figure 9. Design of sources of plasma flows with a cold cathode
1-water-cooled anode, 2-magnetic core-housing, 3-electromagnet

The ion source with a cold cathode, located at an angle of 30÷60° to the substrate holder, includes a flange, a discharge chamber, a magnetic circuit, an electromagnetic coil, a cooled insulated anode and a leak of working gases, such as Ar, Kr, N_2, CF_4.

The ion source has a ring anode located in the discharge chamber, the inner part of which has a 3÷4 mm fluoroplastic insert. The discharge chamber is formed by a magnetic core made of steel with a wall thickness of up to 10 mm, which has an electromagnetic coil (about 300 turns) on the outer part. The magnetic core forms a magnetic gap above the anode with a gap width of about 6 mm. A working gas leak is introduced into the discharge chamber.

The power supply includes a power supply unit for the electromagnetic coil with a current of up to 3÷4 A. To power the anode, a controlled step-up transformer with a rectifier is used, providing a supply voltage of 3.5÷4.0 kV with a discharge current of up to 500÷600 mA.

After creating a vacuum degree of about 10^{-3} Pa, the working gas pressure is set to about 210^{-1} Pa. A current of up to 2 A is supplied to the electromagnetic coil, and a high voltage of +3÷4 kV is supplied to the anode, resulting in a beam-plasma discharge with a tubular plasma flow with a diameter of about 80 mm. A plasma beam with ion energy in a flow of 0.5÷4.0 keV processes the surface of the substrate holder. If a device creating a magnetic field (an electromagnetic coil) is installed in the path of the ion flow, then the annular flow can be contracted.

For microwave plasma treatment of surfaces with excited particles with minimal charge action, a microwave (f=2.45 GHz) plasma generator with an electrodeless gas discharge based on electron cyclotron resonance (ECR) was developed.

The device contains a lamp power supply, a waveguide path with a piston in the rear part of the waveguide, a sealed quartz window 10 mm thick Ø 90 mm, a cylindrical plasma chamber with a quartz tube liner, a working gas supply unit, 3 electromagnetic coils, removable mesh electrodes with a power supply. The device is connected to the vacuum chamber through a flange. In front of the microwave plasma source, a rotating container with

samples is located in a vacuum chamber. The container is supplied with voltage in the range of 0÷1500 V at a load current of up to 500 mA.

To increase power, a water jacket is used to cool the anode of the generator lamp. The generator tube antenna enters the cylindrical waveguide at a distance of about half a wavelength from the plane of the piston. The length of the plasma chamber Ø 90 mm is 200 mm.

The plasma chamber includes a working gas leak valve type VN-1.6, connected to a reducer and a gas cylinder.

On the outer part of the plasma chamber there are movable electromagnetic coils, each of which is a thin-walled cooled coil with copper wire (about 1000 turns Ø 1.8 mm). The coils are powered by 3 independent DC sources (up to 12 A each).

The plasma chamber is connected to steel flanges, between which removable electrodes on metal-ceramic insulators are fixed. Multi-cell removable disk electrodes made of tantalum and stainless steel 0.5-1.0 mm thick with 150-200 holes Ø 2-3 mm were used.

The power source includes a DC power supply, which provides an adjustable voltage at the cathode of the microwave lamp minus 3-4 kV due to a thyristor regulator at currents up to 300-350 mA and smooth control of the cathode heating. The electromagnet power supply consisted of three groups representing controlled mains voltage rectifiers, providing currents up to 12 A at voltages up to 80 V. The grid bias unit provides voltages up to 100 V at load currents up to 200 mA.

After obtaining a vacuum degree of about 10^{-3} Pa in the vacuum working chamber, working gas (Ar, O_2, N_2, CF_4) was supplied to the plasma chamber and the pressure was set in the range of 5^{10}-2^{-10} Pa. Then the electromagnetic coils were turned on and the selected magnetic field configuration was established. A magnetic induction value of about 900 Gas was achieved at currents of about 9.5 A. The power supply of the microwave lamp was turned on within the operating power of up to 800 VA (the anode current was regulated). Electron cyclotron resonance (ECR) conditions were created in the plasma chamber. The plasma parameters depended on gas pressure, magnetic field configuration, and absorbed microwave power.

Research into the operation of the device showed the following. As is known, the current density and concentration of radicals from a plasma source are proportional to the electron concentration n_e and $\sqrt{T_e}$, and their increase is associated with the efficiency of microwave power absorption. To obtain a high-current source and a high concentration of radicals in the plasma, large values of n_e and T_e are required, which can be achieved due to the high efficiency of microwave power absorption.

Studies of the operating modes of a plasma generator at constant power for such working gases as O_2, N_2, Ar, CF_4 have shown that plasma under ECR conditions is effectively formed in the pressure range 210^{-2}÷100 Pa (~10^{-4}÷1 mmHg) at magnetic field strengths from 600 to 1100 Gs.

Studies of the current level on the substrate have shown that at a working gas pressure (O_2, N_2, Ar) of the order of 10^{-1} Pa and constant power in the case of a magnetic field distribution uniformly or with two maxima at the beginning and end of the plasma chamber, current densities reach ~1.0- 1.2 mA/cm^2 at voltages up to ±100 V.

An increase in the magnetic field does not have a significant effect on the electron and ion current densities. For a one-sided magnetic trap with a gradient against the direction of microwaves (grad H>0, the magnetic field is greater at the microwave input window), the current densities from the plasma torch, all other things being equal, are significantly lower compared to a uniform magnetic field. The densities of electron and ion currents do not exceed 0.2 mA/cm^2 and weakly depend on the magnitude of the field gradient, which indi-

cates a low concentration. Quite interesting is the configuration of the magnetic field with a one-way magnetic mirror at the plasma torch output (grad H‹ 0 microwave wave moves in the direction of increasing magnetic field). In this case, the absolute value of the current density is higher than for a uniform field and reaches 2.0 mA/cm^2, possibly due not only to collisional cyclotron absorption and the influence of a magnetic mirror.

In general, the ion current density on the samples depends on the applied voltage and working gas pressure (39-43). Maximum current densities are observed at pressures of the order of 10^{-1} Pa and voltages of 1000 V and higher. For pressures of 1.0-5.0 Pa, currents decrease by at least 2-10 times.

Thus, by changing the parameters of the microwave plasma torch, the configuration and magnitude of the magnetic field, one can effectively control the energy and density of the ion flux. Research has shown that the energy and concentration of electrons depends on gas pressure. Both parameters have a maximum in the range of 510^{-2}÷1,510^{-1} Pa. The electron energy is ~8 eV, and their concentration reaches 510^{10} cm^{-3} at the device output (L=40 mm).

There is also a method of deposition of nano coatings, which uses the sputtering of materials with laser radiation. Part of the vapor phase of the material, obtained using thermal laser evaporation, is ionized and turns into a plasma state due to the excitation of a glow discharge between the evaporator and the substrate (coated product).

Charged particles under the influence of an electromagnetic field are accelerated and move towards the substrate with sufficiently high energy (0.5-1.2 keV). As a result, the resulting coating has good adhesion and high density.

The process is carried out at a residual pressure of 0.1-1.0 Pa. The advantages of the method also include the relatively low heating temperature of the substrate and the relative simplicity of the process. However, the scattering effect and simultaneous deposition of ionized and non-ionized particles do not always ensure good uniformity and homogeneity of coatings. The substrate must be electrically conductive. Any evaporation method can be used to evaporate the material, but the most promising is usually the use of laser radiation. In the latter case, it is quite easy to obtain coatings consisting of several nanolayers of various materials (44).

VACUUM ARC EVAPORATION

The most effective and advanced electric-discharge devices for ion deposition are the widespread vacuum-arc evaporators with a cooled cathode. Vacuum arc sputtering has become widely used in technological processes after solving the problems of stabilizing the position of cathode spots on the surface of the sputtered cathode (45-52). This is achieved, for example, by surrounding the water-cooled cathode with an auxiliary screen and using magnetic fields. It has been established experimentally that cathodes made of working materials should be made in the form of a truncated cone with an inclination angle of about 7° and placed in a solenoid with an induction of about 0.01 T. Vacuum-arc evaporation devices are distinguished by their simplicity of design, high rate of evaporation of materials, and high (almost 100%) degree of ionization of the flow of evaporated material. In general, the ion deposition device for the ion bombardment condensation process is located in the working chamber and includes an insulated water-cooled cathode, a screen, a cooled anode, an electromagnetic coil, an ignition electrode, and an insulated substrate holder for the workpieces. Typical mode of cathode sputtering after ignition of a vacuum-arc discharge: discharge current range 100÷300 A, voltage range 10÷60 V. In the first phase, a negative

potential from several hundred volts to several kilovolts is applied to the workpieces and the surface is cleaned in cathode sputtering mode. After this, the potential is reduced to tens of volts and the coating is formed in the selected mode. In plasma (vacuum-arc) accelerators, streams of particles with controlled high energies are generated. The proportion of ions in the total material flow can be quite high (60-95%). Applying potential to the material being processed allows you to regulate the energy of the deposited particles.

The design of a vacuum-arc evaporator for metals is shown in more detail in Figure 10.

With increased energy, this allows the surface layer of the material to be treated with ions and ensure high adhesion of coatings. Cleaning the surface before deposition of coatings is also easily accomplished in these devices (53, 54).

In plasma accelerators, stable combustion of the discharge is usually maintained by evaporation of the material of the cooled cathode. In this case, the arc discharge burns in the form of separate cathode spots moving along the surface. The diameter of the spots is several microns, and the current density reaches 106-107 A/cm^2.

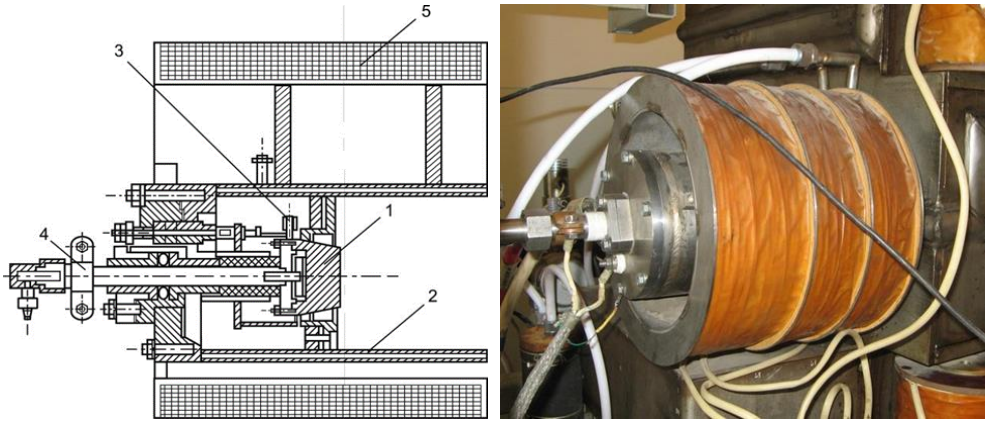


Figure 10. Device for vacuum-arc evaporation of materials
1-sprayed water-cooled cathode, 2-cooled anode, 3-igniting high-voltage electrode, 4-cathode contact, 5-electromagnetic coils

Material (metal) ions are generated in the form of a high-speed cathode jet when the surface is eroded. The cathode erosion products contain a microdroplet fraction (droplet size of the order of 1-10 microns), material vapors and ions, the share of which reaches 90%. The presence of a microdroplet fraction in some cases significantly worsens the quality of coatings.

To ignite a low-voltage discharge in the electrode vapor in a vacuum, initiation of arc development is necessary. To do this, a conducting medium (plasma, which produces field emission from the cathode) is temporarily created in the cathode-anode gap. The plasma cloud is obtained through mechanical contact with an additional electrode. At the point of contact, a current arises and the zone heats up until the metal evaporates. When the contact is broken, a plasma cloud appears, the ions of which initiate the release of electrons from the cathode. To produce an arc in this design, current was passed between electrodes along the surface of an insulator on which a conductive coating was previously applied. The coating evaporates and ionizes in the breakdown zone.

After ignition, the arc burns, forming chaotically moving micro spots on the electrode. A magnetic field was used to stabilize the arc at the end of the cathode. In this case, the

current passing through the spots interacts with the field, as a result of which the spot moves, the plasma rotates, and the torch is focused along the accelerator axis. The interaction of currents with a magnetic field causes the effect of increasing the ionizing ability of electrons and ionization of material vapors, as well as the effect of "additional acceleration" of the plasma under the influence of the axial component of the magnetic field.

Effective plasma focusing is observed already at a magnetic induction of about $5 \cdot 10^{-3}$ T. The processes of plasma generation in the area of cathode spots are practically independent of the magnetic field induction and are determined by the type of cathode material. By applying a negative potential to the substrate, you can further accelerate the ionic component of the flow and clean the surface to increase the adhesion of coatings (55, 56).

Due to the instability of the vacuum arc in devices with a cold cathode at low discharge currents, plasma accelerators must be operated in continuous mode at a power of more than 1 kW.

By applying a negative potential to the substrate, you can further accelerate the ionic component of the flow and clean the surface to increase the adhesion of coatings.

Vacuum-arc ion deposition devices have found application in serial industrial installations such as "Start" and "Bulat".

Devices and installations are used to form durable protective coatings on tools. The main disadvantage of arc evaporators is the high temperatures of the evaporator and the presence of a droplet fraction in the flow of evaporated material (57-60). The size and number of droplets in the flow depend on the cathode material and the evaporation mode; on average, the droplet diameter is 1-10 μm. This significantly limits the use of arc evaporators in microelectronics and optics.

Another type of vacuum-arc evaporation of materials has also been studied, providing the evaporation of metals without a droplet fraction from a self-heating crucible-cathode. At the initial moment, a conventional discharge is ignited on a cold cathode with micro spots, after which ion treatment increases the temperature of the cathode and, if the average current density on the integrally hot cathode exceeds the critical value of 10-100 A/cm^2, the saturated vapor pressure is sufficient to maintain a distributed arc discharge with a degree of ionization of metal vapors of about 100% (in particular for Cu, Mo, Cr).

APPLICATION OF FUNCTIONAL COATINGS

Vacuum deposition coatings are used in the production of electronic devices such as microchips, LEDs, and solar cells. The process is useful in coating the metal patterns, which are essential for the device's proper functioning. The thin-film deposition process is also used to manufacture thin-film transistors, which are used in flexible displays and sensors.

The vacuum deposition process is also useful in creating decorative coatings, which are used in a variety of applications such as jewelry, automotive finishes, and architectural elements. The process allows the deposition of metallic, ceramic, and organic coatings, which can be customized to create desired patterns.

Another major field of applying thin film technology to the substrate is for cutting tools. Today, the manufacturing of mechanical parts of machine parts requires special machining. High adhesive properties are required to ensure longevity of the cutting tool. Using deposition technology on cutting tools increases corrosion, wear resistance and adhesion life of the tool.

One example of the vacuum deposition process in practice is the applications of electron beam evaporation in the creation of optical coatings for laser technology. In this process, an

electron beam is used to heat the material, which then evaporates and deposits on the substrate to create a thin film with excellent reflectivity properties.

CONCLUSION

Thus, based on the conducted review studies, the following conclusions can be drawn:

- An effective method for applying thin films to a surface is thermal evaporation, despite complex modeling of technological processes.
- Deposition methods are selected based on the chemical and physical properties of the material (refractory, complex alloys, evaporation temperature).
- The ability to change the composition, structure and properties of coatings, obtaining multilayer coatings of various thicknesses down to nano-sized particles by changing deposition parameters increases the properties of the material and makes the process unique.

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