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Materials Science

Research and Development of an Innovative Planar-Rotational Magnetron Sputtering Device for Obtaining Advanced Materials

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(Presented by Academy Member Giorgi Japaridze)

The paper includes information about planar-rotational magnetron sputtering device for obtaining mono- and multi-component thin coatings and nanostructured materials, its research, the development of new innovative construction, its manufacture and its use in laboratory research, and various fields of production. The planar-rotational magnetron sputtering device compared to the stationary analog is compact, has an effective cooling system, and also has a high utilization rate of an expensive target material. As a result, we accept the uniform erosion zone of the disk target and the stability of the plasma, the arrangement of permanent magnets in the rotating magnetic block along the trajectory of involute, and as a result, the creation of a closed magnetic field of complex configuration. The design of the device makes it possible to control the configuration of the magnetic field, the frequency of rotation of the magnetic block, and the distribution of the discharge current density on the surface of the disk target, which significantly improves the quality of the obtained advanced materials in optics, biomedicine, renewable energy, quantum technologies – solid-state qubits in the field of synthesis and development of devices operating on quantum effects. *© 2023 Bull. Georg. Natl. Acad. Sci.*

magnetron, target, magnets, erosion, electron

The magnetron sputtering device belongs to a special class of sputtering devices, the technique, and technology of which are widely used for film coating in many fields of science and technic. Since the initial stage of development, the construction of magnetron sputtering devices has been constantly improved. For the first time, the original design of a stationary planar magnetron sputtering device (PMSD) was successfully implemented by American scientists [1-3]. The main characteristics of the PMSD developed by them are the voltage on the electrodes, the discharge current, the density of the ion current on the target, the specific power, the value of the magnetic field induction, and the pressure of the working gas. The stability of the magnetron discharge and the reproducibility of the technological processes of thin film deposition in a vacuum depending on the magnitude and stability of the listed parameters, which are interrelated. In this case, the ion current density is very high and for a system with flat cathode-target is about 200 mA/cm^2. Moreover, the maximum current densities in the central part of the sputtering zone manages to much higher, which reaches to thermal overload of the target, its distortion, and in places of poor contact with the cooled holder, to its melting.

The main elements of the PMSD design are the cathode – target, the anode and a closed magnetic system, which forms a magnetic field of a certain configuration and magnitude on the target surface to create an effective magnetic trap of electrons, the so-called "Treadmill for electrons". The configuration of the magnetic field of the magnetic system of modern PMSD is very simple and has a round or rectangular shape. As the target is sputtered, a deep and narrow V-shaped "groove" is formed on it. This reduces the service life of the target, and the coefficient of using the target material is about 30%. The remaining 70% of the target material will either be recycled or discarded [4].

The formation of an erosion "groove" leads to an increase in the electric field strength on the target surface, and the appearance of the effect of a hollow cathode for secondary electrons (when they oscillate between opposite walls of the groove). As a result, the voltage and power of the discharge, the energy of the ions bombarding the target, the sputtering rate of the target, and, accordingly, the rate of coating deposition are reduced. Despite these shortcomings, stationary PMSD are widely used both in industry and for research purposes to obtain advanced thin-film materials [5-10].

The breakthrough of Georgian scientists in the 80s of the last century should be noted in terms of improvement and the success achieved in this direction. The goal, of course, was to eliminate the shortcomings of magnetron sputtering devices of this type that existed before this period. This is our innovative magnetron sputtering device in a vacuum with a rotational magnetron block, which uses the turbulence of a coolant to rotate a magnetic block.

In this work we present an innovative design of the planar-rotational magnetron sputtering device (PRMSD), which contains an anode, a cathode assembly with a sputtered target in the cavity of the cathode assembly, a rotating magnetic block, a cooling system with a drain hole in the central part of the device. A flange with a hole and a holder of the magnetic system in the form of a disk (cylinder) with blades in the lower part are fixed on the cathode unit [11]. The matrix of permanent magnets is located in a row on both sides of the closed axial line of the involute (Fig.1).

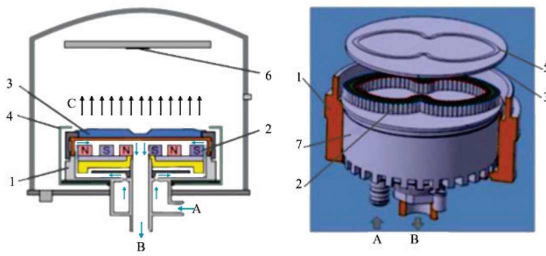
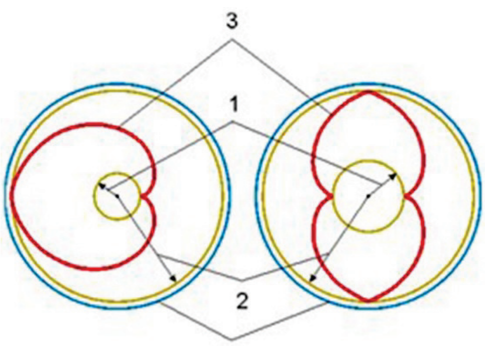


Fig. 1. Construction of PRMSD.
1– cathode assembly, 2 – array of permanent magnets, 3 – annular target cathode, 4 – anode, 5 – plasma, 6 – substrate, 7 – turbine, A – coolant inlet, B – coolant outlet, C – spray of particles.

When a laminar coolant flow is supplied to the inlet of the cathode unit 1 (arrow A) through the flange, the liquid under pressure enters the blades of the magnetic system holder, causes the magnetic block 2 to rotate, from this moment the flow becomes turbulent. This turbulent flow of coolant rises in a spiral to the target holder 3, washes it and the walls of the cathode assembly, heading further to the drain hole (arrow B). Having a large-scale turbulence, the coolant acquires an increased ability to absorb heat, and provides effective cooling of the sputtered target and the cathode assembly as a whole [12]. PRMSD is used in combination with laboratory or industrial equipment for vacuum magnetron sputtering. The compactness of the PMSD facilitates installation in a vacuum chamber in any required position and as a whole, ensures the rapid advancement of technical and technological solutions.

In the presented PRMSD construction permanent magnets in the magnetic block are located along the curve obtained by mathematical calculation, and create a closed magnetic field with a complex configuration:



$$\varphi + C = \frac{\sqrt{r^2 - r_0^2}}{r_0} - \arccos\frac{r_0}{r}, \qquad (1)$$

Fig. 2. Configuration of a closed magnetic field.
1 – r_0 radius of the non-sputtered target zone, 2 – outer radius of the target sputtering zone, 3 – involute line.

where φ and r are the coordinates of the current point of the involute in the polar coordinate system with the pole at the center of the round target; 1 – r_0 – radius of the non-sputtered zone of the target; C is a constant coefficient determined from the condition of involute closure [13]. Graphic images of the involute made according to expression (1) are shown in (Fig. 2). To ensure a uniform erosion zone of the sputtered disk target and the stability of the stationary state of the plasma, its area above the target must be closed and have a constant width. The expression for the axial line that determines the optimal configuration of the plasma region.

When the magnetic block rotates, the vector of extreme magnetic field strength is parallel to the target surface, and the closed erosion zone in the form of an "electron treadmill" covers the entire surface, which ensures a wide, highly uniform erosion zone of the target on its surface and further in volume. In this case, the intensity of ion bombardment of the target surface moves "wave-like", covering all its new unsputtered areas, which are successively subjected to intense sputtering. Thus, a new mechanism of magnetron sputtering of the target surface is implemented, which has a significant impact on the stability of technological processes and the physical characteristics of the films and coatings obtained on a substrate with a complex relief. During sputtering, the profile of the bottom of the target erosion zone is kept flat and uniform on 80-90% of its surface, and further in volume (Figs. 3,4).

a b

Fig. 3. Process of erosion of a disk target.

The initial stage of the process of erosion of a disk target made of Zr (a); Efficient use of the Al target material (b).

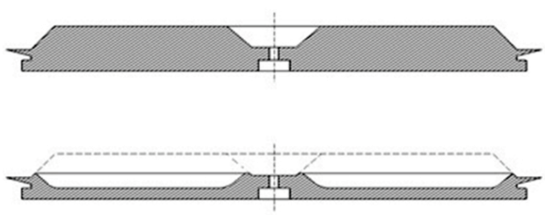


Fig 4. Profile of the target before and after sputtering.

We measured the target depth profile after every 100 kWh of sputtering power. The original target for stationary PMSD and PRMSD had a diameter of 190 mm and 18 mm thick. Starting from the target surface from the initial unsprayed plane, the sputtering depth was measured every 100 kWh of sputtering power. A graph of the dependence of the depth of surface sputtering on the applied power is shown in (Fig. 5). The profile for the PRMSD target is axisymmetric with respect to an axis perpendicular and centered in the plane of the target surface.

and the creation of new technologies. For this purpose, our research is focused on the following: achieve control over the configuration of the magnetic field strength on the target surface, i.e. on the "treadmill for electrons" by adjusting the distance between the poles of the arrays of permanent magnets and, thereby, achieve manage

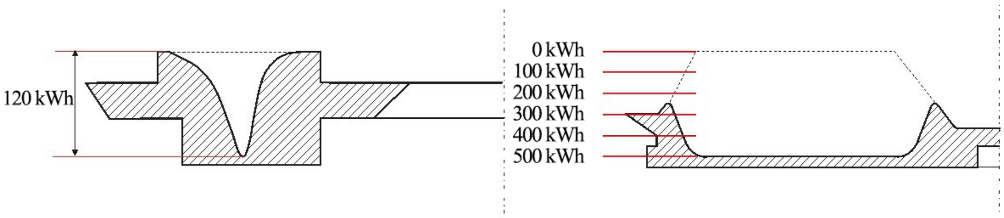


Fig. 5. Target sputtering resource of stationary and planar-rotating magnetron sputtering devices, in kilowatt hours.

Thus, a real breakthrough in the field of magnetron sputtering of materials is a new generation of PRMSD, which significantly expand technical and technological solutions in the field of obtaining composite and functional promising materials [14, 15].

The technological base developed and created by us using PRMSD has found its application in one of the areas of semiconductor electronics, such as the obtaining high-quality composite layers for further improvement of GaAs technology. We have developed and tested a TiW/Ag alloy coating to create “under-rail plating”. In this composition, W plays the role of a barrier, while Ti serves to provide adhesion to the contact layer and the SiO_2 layer and improve the contact properties of the composite layer. In this case, the bumps were grown on a layer of silver, which made it possible to exclude such metals as Cu and Au from the technology. The TiW/Ag system was deposited in a single technological cycle which ensured high uniformity of the deposited metal films both in composition and thickness, as well as obtaining a high-quality coating of relief steps [16].

Despite significant progress in this field, there is a need to develop innovative designs of PRMSD, the distribution density of the ion current over the entire surface of the disk target, also improve technological modes of sputtering by adjusting the frequency of rotation of the magnetic block [17].

Innovation device PRMSD provides modes of stable and reproducible results, for example, in catalysis [18,], to obtain modern optical coatings, photoelectric converters, and biomedical coatings with high biocompatibility [19] etc.

It is by us developed the method for obtaining nanomaterials, including highly efficient catalysts, quantum dots, films of nanostructured materials and monodisperse nanopowders, and a magnetron sputtering device for its implementation [20]. The method of formation of nanomaterials in the process of sputtering of the target material includes the formation of a flow of macrodroplets in the active zone of erosion and their cascade fission in the area of the magnetron plasma of a toroidal shape. The formation and electrodispersion of macrodroplets proceeds under the action of intense ion bombardment between the inputs and outputs of magnetic field lines in a closed loop configuration. The configuration of this closed magnetic field circuit with a disk target erosion zone width of 2–5 mm and at high values of the applied power density, provides stimulation of electrical instabilities in the active zone, such as “arcs” or “spokes” [21] and promotes the formation of a magnetron ion plasma electrodispersion of liquid-phase drops from the target. Simultaneously with the sputtered atoms and molecules, macrodroplets fly out from the target surface and enter the volume of the toroidal magnetron plasma. The sputtered atoms and molecules of the target material freely pass through the toroidal magnetron plasma, and macrodroplets from the target material in the volume of the toroidal magnetron plasma are recharged. Further, as a result of the development of the process of Rayleigh or capillary instability in plasma, they undergo cascade fission. The process of cooling and solidification of nanoparticles occurs outside the plasma region in the vacuum space between the target surface and the substrate holder. This eliminates the risk of an increase in the size of nanoparticles as a result of maturation or agglomeration according to Oswald. Rapid cooling of monodisperse nanoparticles formed on the surface of the substrate contributes to the retention of their size of 2-4 nm, spherical shape, and amorphous structure. The proposed magnetron electrodispersion reactor is intended for the synthesis of catalytic materials and for the production of nanomaterials with improved physical properties in the field of nanotechnologies, including quantum dots, thin films of nanostructured materials, and monodisperse nanopowders [22].

In conclusion the PRMSD has the following advantages:

1. Compactness and original design of PRMSD;
2. Efficient cooling of the sputtered target and the cathode assembly as a whole. The coolant flow is also used in the cathode assembly to rotate the magnetic block;
3. A uniform erosion zone of a disk target and a stable stationary state of the plasma are realized due to the arrangement of permanent magnets in the magnetic block along the involute, and the creation of a closed magnetic field of complex configuration on the target surface, during the rotation of the magnetic block;
4. The PRMSD based ion-plasma electrodispersion reactor is designed to convert metal targets into nanostructured materials and can be widely used in quantum technologies – for the synthesis of solid-state qubits and the development of devices operating on quantum effects;

This paper is dedicated to the memory of those who died as a result of Covid 19 and, in particular, to our colleague senior researcher Iosif Gadakhabadze.

მასალათმცოდნეობა

პერსპექტიული მასალების მისაღები ინოვაციური პლანარულ-როტაციული მაგნეტრონული გაფრქვევის მოწყობილობის კვლევა და შემუშავება

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(წარმოდგენილია აკადემიის წევრის გ. ჯაფარიძის მიერ)

ნაშრომი მოიცავს ინფორმაციას მონო- და მრავალკომპონენტიანი თხელი ფირების, ასევე ნანოსტრუქტურული მასალების მისაღები პლანარულ-როტაციული მაგნიტრონული გაფრქვევის მოწყობილობის შესახებ, მის კვლევას, ინოვაციური კონსტრუქციის შემუშავებას, დამზადებასა და გამოყენებას როგორც ლაბორატორიულ კვლევებში, ასევე წარმოების სხვადასხვა სფეროში. სტაციონალურ ანალოგთან შედარებით პლანარულ-როტაციული მაგნიტრონული გაფრქვევის მოწყობილობა კომპაქტურია, აქვს ეფექტური გაგრილების სისტემა და ასევე ძვირადღირებული სამიზნე მასალის გამოყენების მაღალი კოეფიციენტი. შედეგად, ჩვენ ვიღებთ დისკური სამიზნის ერთგვაროვან ეროზიულ ზონას და პლაზმის სტაბილურობას. რადგანაც მუდმივი მაგნიტები მბრუნავ მაგნიტურ ბლოკში განლაგებულია ევოლვენტის წირის ტრაექტორიის გასწვრივ, იქმნება რთული კონფიგურაციის ჩაკეტილი მაგნიტური ველი. ინოვაციური მაგნიტრონული გაფრქვევის მოწყობილობის კონსტრუქცია შესაძლებელს ხდის მართოს მაგნიტური ველის კონფიგურაცია, მაგნიტური ბლოკის ბრუნვის სიხშირე და განმუხტვის დენის სიმკვრივის განაწილება დისკური სამიზნის მთელ ზედაპირზე. აღნიშნული მნიშვნელოვნად აუმჯობესებს მიღებული თანამედროვე მასალების ხარისხს, პლანარულ-როტაციული მაგნეტრონული მოწყობილობის ტექნოლოგიურ შესაძლებლობებს ოპტიკაში, ბიომედიცინაში, განახლებად ენერგეტიკაში, კვანტურ ტექნოლოგიებში – კვანტურ ეფექტებზე მომუშავე მყარი კუბიტების სინთეზირებისა და შემუშავების სფეროში და სხვ.

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