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Planar Magnetron Sputtering Device: A New Generation of Magnetron Sputtering Design and Technology

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Abstract: We have developed the original design of the planar magnetron sputtering devices, where a turbulent flow of cooling liquid is created in the cathode assembly to rotate the cathode block. Under pressure on the blade of the magnetic system holder, the flow of liquid causes to rotate the entire magnetic assembly. Rotation of the magnetic system under the sputtered circular target cathode ensures synchronous movement of the closed magnetic field along its surface. The configuration of the magnetic system, calculated by the mathematical method, taking into account the magnetic field closedness, makes it possible to obtain, on the maximum possible target area, a magnetic field vector parallel to its surface and, therefore, a maximum uniform area of erosion. The intensity of ion bombardment on the surface of the target "undulates", embracing all its new non-dispersed areas, and they alternately undergo intensive sputtering. Herewith a new physical mechanism of magnetron sputtering of the target surface is realized, which has a significant effect on the stability of technological processes and the physical characteristics of the resulting films. In addition, by adjusting the distance between the opposite poles of the permanent magnet arrays, it is possible to change the configuration of the magnetic field on the target surface. This makes it possible to regulate the distribution of the intensity of ion bombardment on the target surface, which, in one's turn, together with the regulation of the rotation rate of the magnetic system, opens new possibilities for controlling the technological modes of atomization.

Key words: Magnetron, array, magnets, circuit, erosion.

1. Introduction

The main line of development of magnetron sputtering up to the present time has been associated with the transition to planar magnetron sputtering systems in the 70s of the past century. The use of magnetron sputtering in coating technology was first proposed by F. Penning [1] in 1935 and patented in several countries. For sputtering it was intended to use discharge systems with an axial magnetic field of a normal magnetron type and a Penning cell type. Subsequently, vacuum pumps and vacuum gauges were created on their basis, but initially the discharge in a magnetic field was not virtually used for the coatings.

In the sixties, in connection with the need for the development of film microelectronics technology, experiments were again conducted on the development and investigation of the sputtering of materials in a magnetron discharge. The initiators of these developments were W. D. Gill and E. Key [2, 3] and K. Wasa and S. Hayakawa [4, 5]. In general, they used cylindrical coaxial systems of the normal and inverse magnetron type.

In 1973 J. F. Corbani [6] and in 1974 J. S. Chapin [7, 8] proposed the design of magnetron sputtering devices in which a radial magnetic field was created on the surface of a target cathode. In order to increase the efficiency of the device, the magnetic system was equipped with a magnetic circuit, by means of which the magnetic field lines formed a closed "tunnel vault" above the surface of the target cathode, where a magnetron discharge with a closed azimuthal drift of electrons occurred and was maintained. These designs were a prototype of modern planar magnetrons,

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including the PMSDs (planar magnetron sputtering devices) proposed by us in this article.

Despite the great advances in the design and study of the design of magnetron sputtering devices and magnetron sputtering technology, it cannot be said that all the problems that are inherent for this method have been solved. For example, a cathode assembly includes a closed loop permanent magnets array and is located in a fixed position to the target cathode, thereby creating conditions for an inhomogeneous intensity of the ion bombardment of the target cathode and obtaining an erosion area of narrow annular shape. Uneven wear of the target leads to instability in the technological processes of sputtering, unevenness in thickness and composition of the coatings obtained, as well as to incomplete use of the target material.

The main disadvantage of modern planar magnetrons is the low percentage of use of the target material (no more than 50%-60%). The narrow and deep shape of the erosion area of the target creates a condition for a high thermal load per unit area of the target and instability of technological parameters of sputtering due to its wear. During the depletion of the target and the formation of a deep erosive ditch in it, the parameters of the magnetron discharge and the conditions for the deposition of coatings change. The formation of an erosive ditch leads to an increase in the electric field strength at the target surface and to the effect of a hollow cathode for secondary electrons (with their oscillation between opposite walls). As a result, the discharge voltage, the discharge power, the energy of the ions bombarding the target, the rate of its sputtering and the deposition rate of the coatings decrease. The deepening of the erosive ditch also alters the conditions for the distribution of the flow of sputtered particles and leads to the focusing of high-energy heavy particles going to the substrate—the neutralized argon ions reflected from the target and negative ions of the reactive gas. As a result, heterogeneities occur in the coating, especially if the coating or substrate exposes to high-energy particles. In the case of reactive sputtering, all this affects the synthesis process and the composition of the coating material [9].

One of the promising directions in the development of magnetron sputtering is the creation of a system with a variation of the magnetic field in magnitude and configuration. Such a device allows expanding the target erosion area, stabilizing sputter parameters and characteristics of sputtered films as far as the target wears out, improving economic performance, etc.

A magnetron sputtering device is known where the coolant flow performs two functions: participates in the heat takeoff from the target during the sputtering process and rotates the magnetic block with a multi-bladed turbine wheel [10, 11]. All those features complicate considerably the design of the apparatus and possibility of efficient cooling of the cathodes unit. The use of a hydraulic drive that provides the movement (rotation) of the magnetic system made it possible to simplify the design of the magnetron, since there was no need for external additional mechanisms (electric motors, eccentrics, etc.). In addition, the search was undertaken to optimize the configuration of the magnetic field by applying an empirically obtained magnetic system of special shape, which allowed achieving a buy-to-fly ratio up to 80% in the case of a circular target [12]. In all these magnetrons, the traditional direct cooling system of the target cathode is used by a laminar flow of circulating fluid flow, which does not allow exceeding the maximum cooling efficiency for such systems, and consequently, the level of electric power supplied.

Currently, the following tasks are relevant to improve the technological and technical-economic parameters of magnetron sputtering devices in a vacuum: increasing the deposition rate and the degree of uniformity in composition and thickness of multi-component films on a surface with a complex relief; increasing in stability and degree of controllability of technological processes.

2. Contents

The main directions of improving the design of a planar magnetron are: the creation of a cathode assembly with effective cooling of the target cathode; reduction of the total mass and dimensions; the development of a magnetic system with the configuration of a closed magnetic field, in the rotation of which a significant expansion of the erosion area is ensured, thus increasing the buy-and-fly ratio of the target material and the quality of the films and coatings obtained; simultaneously, the reduction of the thermal load per unit surface area of the target cathode; increasing stability and degree of controllability of the technological process of magnetron sputtering, etc.

An analysis of modern magnetron sputtering methods and devices has shown that the most effective solution of these problems is achieved by creating a PMSD with a rotating magnetic block, provided that a plasma region is formed that can provide a uniform area of erosion of the target material throughout the entire volume.

In 1983 and 1984, we developed an original design and manufactured prototype PMSD with a rotating magnetic unit, where a stream of cooling liquid is used in the cathode assembly to rotate the magnetic unit [13, 14]. Rotation of the magnetic system under the target leads to a synchronous movement of the closed magnetic field on its surface. The application of a special mathematical method made it possible to create a closed magnetic field the intensity vector of which is parallel to the target surface almost in the entire region above the target. This allowed obtaining a uniform area of erosion on the maximum possible area of the target.

According to the Georgian patent [15] and the International patent application [16], in the PMSD with the adjustment of the distance between opposite poles of permanent magnet matrices developed by us in 2015, it became possible to regulate the configuration of the magnetic field above the target and, accordingly, to regulate the distributions of intensity of ion bombardment on the target surface. This, together with the possibility of regulating the rotation rate of the magnetic system, reveals good opportunities for controlling the technological regime of magnetron sputtering.

Fig. 1 shows a chart of a PMSD with a rotating magnetic block. The target holder 4 is connected to the cathode assembly 1 with a gasket and a nut. The anode 5 is isolated from the cathode. In the cavity of the cathode assembly 1, under the holder of the sputtered target 4, there is a rotating magnetic unit consisting of a magnetic system holder with blades in the lower part 2 and a magnetic circuit 6 with a permanent magnet array 3 fixed on it, the axial line of which has a certain configuration. The magnetic block with the help of a nut is fixed on the cathode assembly 1 through the fluoroplastic adapter sleeve. A flange with holes is attached to the bottom of the cathode assembly 1 and provides a direction of flow of cooling liquid to the blade of the magnetic system holder 2. The array of permanent magnets of cobalt and rare earth elements alloy is arranged linearly in both sides

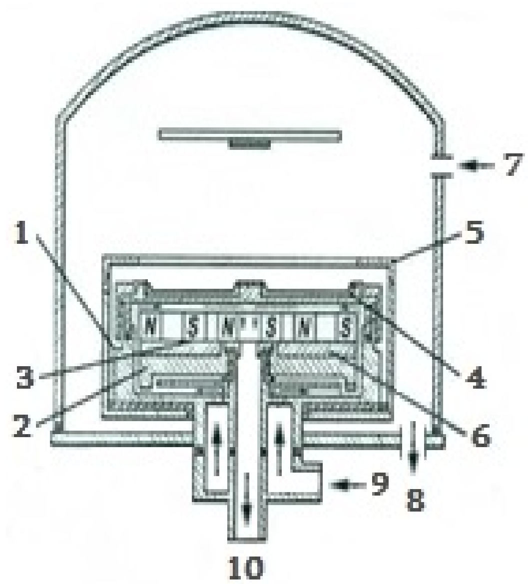


Fig. 1 Vacuum sputtering device with PMSD.
1—cathode assembly, 2—holder of the magnetic system, 3—matrix of permanent magnets, 4—target, 5—anode, 6—magnetic conductor, 7—process gases (Ar, N_2, O_2), 8—to vacuum pump, 9—coolant inlet, 10—coolant outlet.

of the closed center line and with opposite poles is faced the magnetic circuit 6.

When the cooling liquid flow is fed through the flange 9 to the cavity of the cathode assembly 1, the liquid under pressure falls on the blades of the magnetic system holder 2 and rotates the entire magnetic unit. The fluoroplastic sleeve ensures the rotation of the magnetron unit in a liquid medium with minimal friction. The cooling liquid rises upward spirally toward the target holder 4, flows it over and then goes to the drain hole 10. Due to the movement of the cooling liquid in the cathode assembly with large-scale turbulence (instead of laminar movement or, at best, the movement with small-scale turbulence), the cooling liquid in the cathode assembly acquires an increased heat transfer capacity (approximately 3-4 times), thereby effectively cooling the sputtered target and the cathode assembly as a whole [13].

To ensure a homogeneous erosion area of the sputtered cathode and the stability of the stationary state of the plasma, its region above the target must be closed and have a constant width. The curve of the centerline, which determines the optimum configuration of the plasma region, is expressed by the formula:

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

where φ and r are the coordinates of the current point of the evolvent in a polar coordinate system with a pole in the center of the annular cathode, r_0 is the radius of the non-sputtered cathode zone 4 (Fig. 2), C is the constant coefficient, determined from the condition of the evolvent closedness. When $r = R, \varphi = \pi/n$. R is the outer radius of the target sputtering zone, $n = 1, 2, 3, \cdots$[14].

Such a design of the magnetic system, in the case of using any rotation mechanism, enables to obtain, on the maximum possible area, a magnetic field vector parallel to the target surface and, consequently, a maximum uniform plasma zone 7 (Fig. 2). The frequency of the motion of the undulating intensity of the ion bombardment on the surface of the target in one cycle of rotation of the magnetic block, with the configuration n = 2, will be equal to 4. In such displacement, a new physical mechanism of magnetron sputtering is realized which has a significant effect on the stability of technological processes and the physical characteristics of the produced films and coatings on the substrate, including those with complex relief.

The volume of the vacuum chamber of the sputtering device (Fig. 1) is evacuated to a pressure of 10^{-4}~10^{-5} Pa. Then coolant is supplied to the PMSD and a rare gas of argon and a reactive gas are injected into the vacuum chamber by reactive sputtering to a pressure of 0.27-1.30 Pa. When a constant (or pulse) voltage is supplied between the anode and the target cathode, plasma 7 (Fig. 2) flashes along the contour of the arrangement of the permanent magnet arrays, the configuration of which repeats the configuration of the

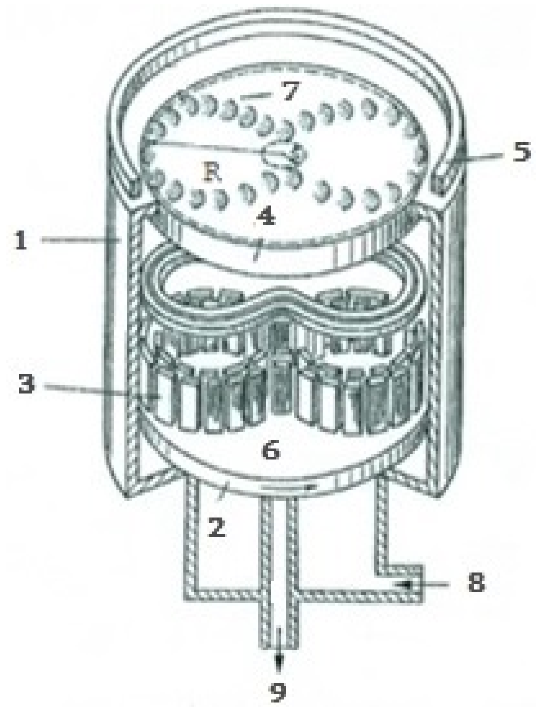


Fig. 2 Construction of PMSD with rotating magnetic block.
1—cathode assembly, 2—magnetic system holder, 3—array of permanent magnets, 4—annular target cathode, 5—anode, 6—magnetic conductor, 7—plasma (area of erosion), 8—coolant inlet, 9—coolant outlet.

centerline of the closed magnetic field. Under the influence of the flow of cooling liquid, the cathode assembly rotates at a rate of up to 80 rpm. The plasma area (erosion area) moves synchronously with the magnetic system and covers all the new non-sputtered areas of the target and alternately undergoes intensive sputtering. As a result, the erosion area of the target expands, the thermal load per unit area decreases, which reduces the probability of curvature of the target as far as it wears out [17].

The main advantages of the PMSD with the rotating magnet assembly developed by us are: the compactness of the devices; significant increase of the buy-and-fly ratio of the target material (up to 70% in the industry, up to 90% in the laboratory conditions); effective cooling of the sputtered target and cathode assembly as a whole; 3-4 times increase of maximum allowable power on the target; 3 times expansion of the target erosion; flatness of the sputtered target bottom; high homogeneity of films condensation by thickness and sputtering of structure relief on the substrate surface.

For widespread use in the industry, as well as for laboratory use, two types of PMSDs have been developed that are easily integrated into commercially available vacuum equipment. Table 1 shows the main technical characteristics of the PMSD with the rotating magnetic unit which is developed and manufactured by us.

The PMSD developed by us was used first used to modify the vacuum coating unit UVN-2M-2 (Magnetron-1) and the continuous unit 01NI-7-006 Oratorio-5 (Magnetron-2) for their wide use in production.

The vacuum coating unit UVN-2M-2 coming with Magnetron-1 (Fig. 3) was used to obtain platinum films on silicon wafers with structures of integrated circuits up to 100 mm in diameter. The design of the vacuum unit also allows for carrying out heat treatment cycles to form platinum silicide in the windows of contact pad in the integrated circuit structures. The above design solution of the under-lid unit is designed for small-scale production of VLSIs (very large scale integrations), as well as for wide application in research laboratories.

The photo (Fig. 4a) shows a set of a cathode assembly with a factory-made target made of aluminum from the continuous unit 01NI-7-006 "Oratorio-5" before its commissioning. The narrow and deep annular area of erosion of the target is of V- or U-shape obtained in the process of wear-out (Fig. 4b).

The authors [18] note that a constant change in the configuration of the target erosion area is a factor hampering the modeling of its profile.

The shape of the target surface (Fig. 5) can be explained by the non-uniformity of the plasma localization above it, which in turn is due to inconsistency in the ion current density. The erosion area of the target is therefore directly proportional to the ion current density, with the lowest point in its topography coinciding with the highest sputtering rate, whereas at the highest points the rate is zero. This means that in effect the sputtering rate can be considered directly proportional to the topography of the erosion area.

On the basis of the computer simulation results presented it can be said that increasing the erosion area has a negligible (< 1%), but nevertheless positive, effect on the uniformity of a magnetron sputtered coating. This, of course, assumes that the entire substrate is within the area of erosion. The development of deposition parameters for obtaining a desired uniformity therefore needs to consider not just the erosion area and the sputtering rate distribution, but

Table 1 Main technical characteristics of the PMSD with the rotating magnetic unit.

Type of magnetron	Supplied power, kW	Maximum current, A	Dimensions (diameter and thickness) of the target, mm	Dimensions (diameter and height) of the device, mm	The diameter of the hole in camera, mm
Magnetron-1	3	5	100 ×(3 ÷ 10)	120 × 160	28
Magnetron-2	6	13	192 ×(16 ÷ 20)	200 × 180	45

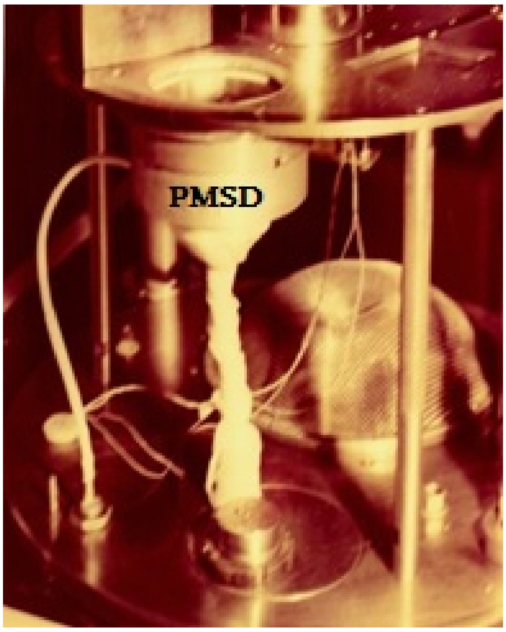


Fig. 3 The under-lid unit of vacuum coating device UVN-2M-2 coming with Magnetron-1.

also the fact that the increase in erosion area over time will improve the coating uniformity.

Fig. 6 shows a modernized cathode assembly and a sputtered target from Magnetron-2. One can clearly see one of the main advantages of the PMSD developed by us, this is the uniform and flat bottom of the erosion area of the sputtered target. Obviously, with such a constructive solution of the PMSD, where the erosion area profile is not distorted, it is easy to predict the target erosion area shape during the sputtering process using computer simulation.

On the basis of the presented set of technological equipment, the production technological route and the technology of formation of VLSI circuit contacts and interconnections based on the PtSi-TiW-Al system [19] were developed, as well as the technological route of sub-bump metallization for hybrid X-ray detectors on the plates of semi-insulating GaAs [20].

Platinum (Pt), silver (Ag), composite material from special purity titanium-tungsten (TiW) and aluminum (Al) were used as the sputtered material in the developed technological routes. Table 2 shows the design and some characteristics of the targets used.

(a) (b)

Fig. 4 Set of the factory-made cathode unit with a target made of aluminum from the continuous unit 01 NI-7-006 Oratorio-5; (a): cathode assembly with magnetron before sputtering, (b): target after sputtering.

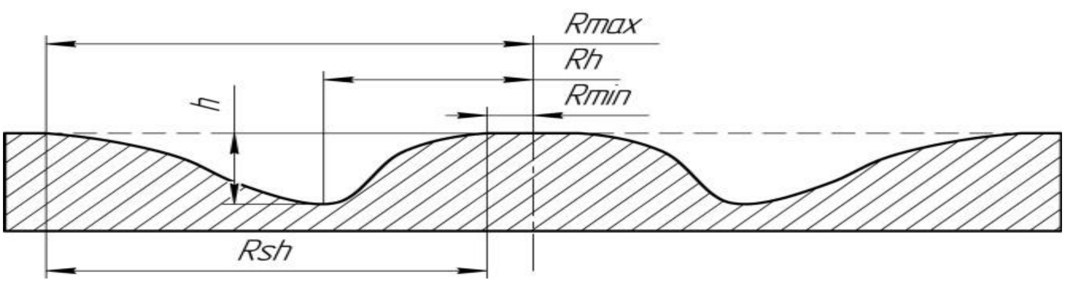


Fig. 5 Erosion area of a magnetron sputtering source target: R_{max}—peak radius; R_{min}—minimum radius; Rh—distance to the lowest point; Rsh—width of erosion area; h—depth of erosion area.

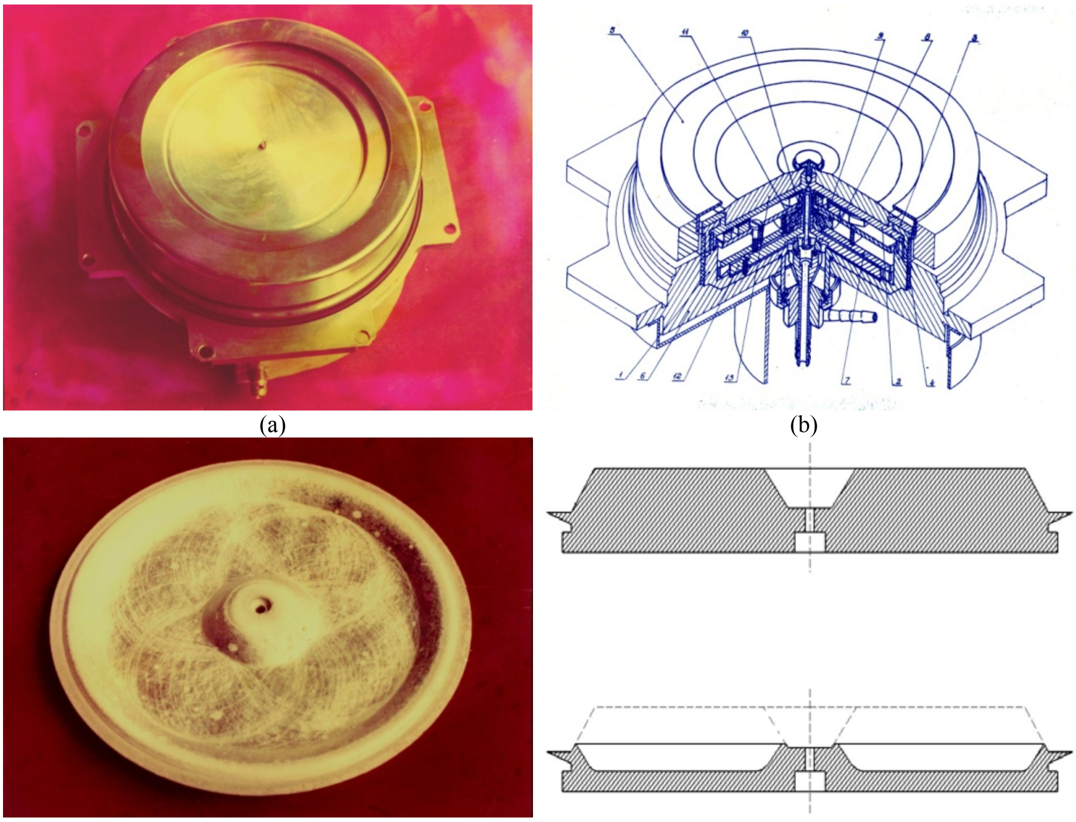
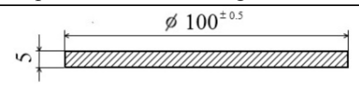
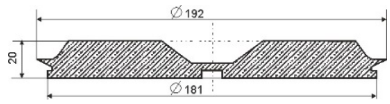
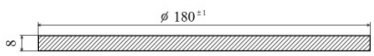
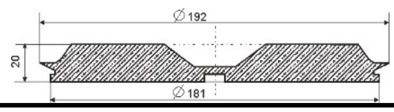


Fig. 6 (a): Photo of the cathode assembly with an aluminum target from the continuous unit 01NI-7-006 Oratorio-5; (b): its design drawing; (c): photo of the worn out target; (d): profile of the target before and after sputtering.

Table 2 Design and some characteristics of the targets used.

№	Type of magnetron	Shape and size of the target, mm	Mass, kg	Material of the targets
1	Magnetron-1		0,842	Platinum
2	Magnetron-2		5,293	Silver
3	Magnetron-2		1,170	Titanium-tungsten
4	Magnetron-2		1,361	High-purity aluminum

It is known that one of the problems of the traditional methods of magnetron sputtering, which occurs when the target is sputtered in the presence of active chemical substances (O_2, N, etc.), is the emergence of a discharge arc on the target surface. At a sufficiently high discharge power due to continuous sputtering, the target material fails to react in due time with the active gas in the narrow erosion area of V- or U-shape, and the target surface, mainly along the central line of the erosion area, does not contain reaction products. Due to the heterogeneity of the ion bombardment at the edges of the erosion area, the ion current density rapidly decreases to a very small value, and the target in these places is not practically sputtered. As a result of interaction of the target with the reactive gas, a dielectric layer produces. Such a process is called “poisoning” the target. The thickness of the dielectric layer on the target is constantly increasing with distance from the central line of the erosion area.

At a continuous magnetron discharge, some of the bombarding ions enter the dielectric layer and charge it. The greatest field strength in the dielectric will be established near the boundary of the erosion area, where the dielectric layer is the thinnest, and the current density of the scattered ions is greatest. Here, a breakdown of dielectric takes place, which leads to the origination of unipolar and bipolar discharges in the form of sparking and arc, respectively. To prevent origination or at least reduce the rate of origination of dielectric layers on the target, a power source automatic protection system is often used, for example, special supply circuits with accumulation of energy that do not allow the input of accumulated energy into the breakdown path [21, 22].

According to the patent of Georgia and the application for the international patent, the design of the PMSD developed by us with the rotating magnetic block in the cathode assembly contains a mechanism for regulating the rotation rate of the magnetic system in the range 0-80 rpm, which is another realized advantage of the developed PMSD compared to the known similar systems of the magnetron sputtering. In addition, in a magnetic system with a closed magnetic configuration, it is possible to control the distance between the poles of array of permanent magnets with opposite polarity in the range 3-10 mm. The magnetic system rotation rate can be controlled either manually or automatically. For specific technological tasks, it is advisable to operate the electric drive with special software, created on the basis of simulation of the target sputtering process and/or experiment data [23].

3. Results

In the early 80s of the past century, the increase in the density of elements on the microchip, the increase in the performance of VLSI circuits with a concurrent decrease in power consumption, as well as the more stringent requirements for reliability, led to an increase in the role of metallization technological processes. The main disadvantages in the production of LSI and VLSI circuits with Schottky diodes are related to the interaction of aluminum with silicon and aluminum electromigration at relatively low current densities. To realize contacts with increased resistance to electromigration, multilayer metallization systems have been developed.

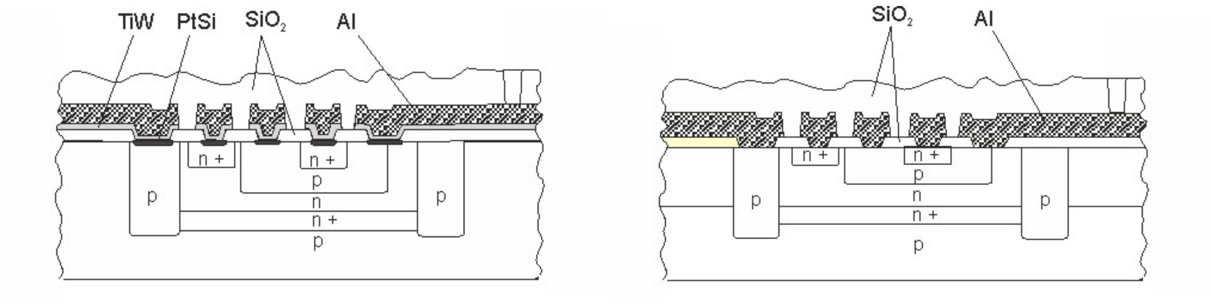
For this purpose a technology for the formation of multilayer metallization of LSI and VLSI circuits with Schottky diodes based on PtSi-TiW-Al was developed. The choice of platinum silicide as a contact material is due to its high barrier to n-type silicon (0.85 eV) and a satisfactory ohmic contact with lightly doped p-type silicon. The choice of titanium-tungsten alloy (the titanium weight fraction in the films was ~10%) is due to the high barrier properties preventing the penetration of aluminum into the contact region.

Based on the PMSD developed by us and using new advanced materials, a technology for the production of LSI and VLSI circuits on the UVN-2M-2 and Oratorio-5 installations was developed. In particular, the technology for successive processes of platinum deposition, silicide formation and processes of application of titanium-tungsten alloys (as a barrier) from the composite target was created. The main technological parameters of the deposition of contacts and interconnections based on PtSi-TiW-Al are shown in Table 3.

The main technological stages of formation of contacts and interconnections in LSI and VLSI circuits are: (1) opening of contact windows to active and passive components located in the silicon substrate body, (2) applying platinum films and heat treatment for the formation of platinum silicide in contact windows, (3) releasing platinum unreacted with silicon, (4) alternate application of titanium-tungsten

Table 3 Main technological parameters of the deposition of contacts and interconnections based on PtSi-TiW-Al.

№	Parameters	Deposition, Pt	Deposition, TiW	Deposition, Al
1	Preliminary evacuation of the hood, Pa	3.5×10^{-4}	1.3×10^{-5}	1.3×10^{-5}
2	Working pressure, Pa	10^{-1}-10^{-2}	10^{-1}-10^{-2}	10^{-1}-10^{-2}
3	Preheating, °C	350	250	270
4	Voltage of the target, V	450	450	450
5	Sputtering current, A	0.4	2	13
6	Sputtering duration, sec	120	350	300
	Ignition in the chamber:			
7	a. temperature, °C	450	400	-
	b. duration, sec	600	300	-
8	Thickness of films, μm	0.04-0.05	0.2-0.25	1.1-1.35



(a) (b)

Fig. 7 Scheme (profile) of the technological route for the production of LSI and VLSI circuits. (a): metallization based on PtSi-TiW-Al, (b): metallization based on aluminum.

and aluminum of the required thickness, (5) formation of the interconnection pattern by precision photolithography methods. These processes enabled to realize a complex technological route of wide application for the formation of contacts and interconnections of LSI and VLSI circuits based on PtSi-TiW-Al, which ensured high reproducibility and operational stability of manufactured electronic products. The proposed scheme (profile) of the technological route for the origination of multilayer metallization of LSI and VLSI circuits with Schottky diodes based on PtSi-TiW-Al (Fig. 7a) practically is similar to the route of LSI manufacture with aluminum metallization (Fig. 7b) and easily fits to the existing cycle of technological production.

The above technical and technological solutions, in addition to saving the target material, made it possible to improve the quality of coating on the relief structures of silicon wafers. The increase in the quality of coating of platinum films and further titanium-tungsten in the contact windows of microchips contributes to a significant improvement in the inverse characteristics of Schottky diodes, especially the diodes without a guard ring. For example, at reverse currents I_r = 10 μA, the voltage drop on the Schottky diodes increased to U_h > 25 V, which is twice the production norm (U_h > 12 V).

In addition, the technological base developed and created by us has found its application in one of the directions of semiconductor electronics, such as the development of detectors of various types of radiation, in particular, X-ray radiation for use in medical diagnostics. For this purpose, hybrid detectors consisting of two parts: GaAs chip with a pixel sensor array and Si chips with reading electronic circuits, are most well developed [24].

An important component of manufacturing hybrid detectors is the process of electrical connection of a sensor chip to a reader chip. This operation is carried out with the help of bump contacts by the method of a flipped chip [25]. The advantage of this method is the improvement of electrical parameters, the increase in reliability and, most importantly, the possibility of a significant increase in the chip density.

The development of the technology for creating bump contacts and under-bump metallization was carried out on plates of semi-insulating GaAs containing sensor matrices. Fig. 8 shows the sequence of technological processes for obtaining bump contacts.

As under-bump metallization, the TiW/Ag alloy was developed and tested, which was applied to the plate by a continuous layer. In this composition, the role of the barrier is performed by W, and Ti serves to provide adhesion to the contact layer and the SiO_2 layer and to improve the contact properties of the composite layer. The TiW/Ag system was applied in a single technological cycle using PMSD based Oratorio-5 unit, which ensures high homogeneity of the applied metal films both by composition and thickness, as well as obtaining good coating of the relief steps.

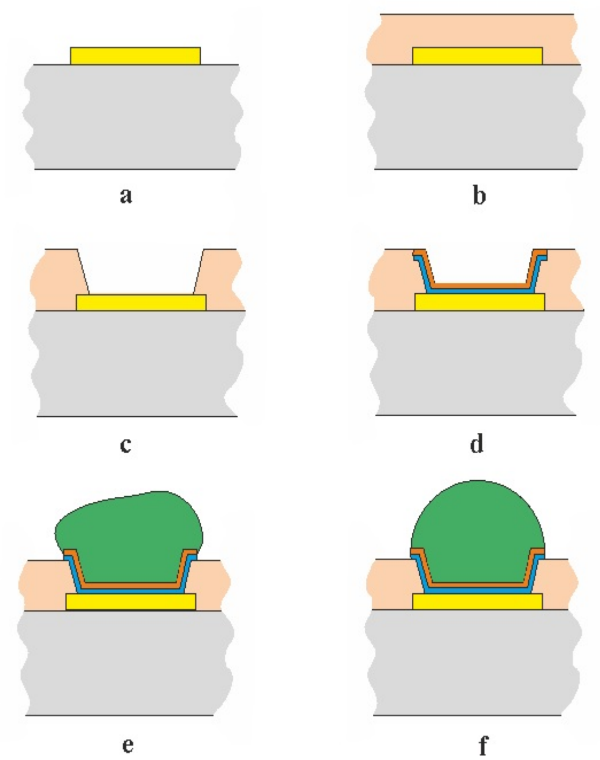


Fig. 8 Sequence of technological processes for forming bump contacts.

a—GaAs plate with metal contacts, b—coating SiO_2 layer; c—formation of windows Ø24 μm in the SiO_2 layer; d—applying the metallized TiW/Ag system; e—deposition of the Pb/Sn alloy in the photoresist windows Ø32 μm, f—Pb/Sn post bend after fusion process.

As we know, for the first time we used the TiW/Ag alloy coating by the magnetron sputtering method to create the under-bump metallization. Thus, the bump is grown on a silver layer, which allows excluding metals such as Cu and Au from the technology [20].

Experiments were carried out on the basis of the UVN-2M-2 vacuum coating unit using Magnetron-1 set and targets from low-resistance semiconductor materials of germanium (Ge), silicon (Si) and zirconium (Zr) to develop a dielectric film technology by the reactive magnetron sputtering method [26, 27].

As was to be expected, the new target sputtering mechanism implemented in the PMSD design significantly changed the physical processes occurring during the reactive magnetron sputtering. For example, when the ion bombardment intensity constantly “undulates” on the target surface in a wide erosion area, it is always possible to create conditions where the target material, even at a sufficiently high discharge power, has time to react with the active chemical gas. As a result of the interaction of the surface material of the target with the gas, a dielectric layer is formed in this region, which, simultaneously with the formation, undergoes the intense magnetron sputtering. In this case, the probability of formation of an undesirable thin dielectric layer (at the boundaries of the erosion area) along the central line of the target erosion area and the probability of formation of a breakdown in the form of sparking or arc is minimal. As a result, there is no need to use an automatic power source protection system.

4. Discussion

However, due to the inadequate measuring equipment and devices, and lack of proper financial support, the authors do not have the opportunity to conduct deeper studies of the technical and technological parameters of the PMSD, which would facilitate for specialists in this field to assess all the advantages of the developed system. New possibilities of the proposed design can be used to solve the constantly emerging new directions in science and engineering that need modern technologies.

5. Conclusions

An original design of the PMSD has been developed, where a turbulent flow of cooling liquid is used in the cathode assembly to rotate the magnetic unit. In the developed design a laminar flow of liquid transforms into a large-scale turbulent flow, which ensures effective cooling of the target cathode and the cathode assembly in whole, and, therefore, significantly reduces the thermal loads per unit of target space and the probability of bend of its shape as it wears out.

The design of the magnetron is remarkable for its compactness, easy installation and replacement. The simplicity of design provides high reliability when operated in production. The configuration of the magnetic system, calculated by the mathematical method, taking into account the magnetic field closedness, makes it possible to obtain, on the maximum possible target area, a magnetic field vector parallel to its surface and, therefore, a maximum uniform area of erosion. The intensity of ion bombardment on the surface of the target "undulates" covering all its new non-sputtered areas, and they are alternately subjected to intense sputtering. As a result, the erosion area of the target expands approximately 3 times.

The new physical mechanism of sputtering implemented in the developed PMSD design in a wide target erosion area provides the creation of conditions where the target material, even at a sufficiently high discharge power, manages to react with the active chemical gas. Due to the "undulation" of the ion bombardment region along the target surface, the formed dielectric layer undergoes intense sputtering. This creates the conditions for reactive magnetron sputtering, where the probability of a transition from a glow discharge to an arc is limited due to the residues of dielectric films on the target surface.

The cathode assembly of our patented PMSD design contains a mechanism for regulating the rotation rate of the magnetic system. The mechanism of frequency control in the range from zero to 80 rpm additionally contains a program control device. The magnetic system of the cathode assembly is arranged to control the distance between the poles, the magnetic group of permanent magnets with an opposite polarity in the range of 3-10 mm that composes the array. These two independent technical parameters of PMSD allow to increasing the degree of controllability of the technological process of magnetron sputtering and, accordingly, the physical properties of the resulting single- and multi-component films and coatings.

The experimental results obtained during tests of PMSD through its long-term operation in production, as well as technological developments performed in research laboratories; show a high degree of development of the original design proposed by us, which in future can serve as a serious alternative to similar modern magnetron sputtering devices.

References

[1] Penning, F. M. "Coating by Cathode Disintegration." Patent USA. 2 146 025 (Priority 28/12/1935, Priority 7.11.1936, Date of publication 7/02/1939), Improved method of disintegration by means of an electric glow discharge. British Patent 476208 (Priority 28.12.1935, Priority 24.12.1936, Date of publication 3.12.1937).

[2] Kay, E. "Process of Cathode Sputtering from a Cylindrical Cathode." Patent USA 3 282 816 (application 10/09/1963, Date of publication 1/11/1966).

[3] Gill, W. D., and Kay, E. 1965. "Efficient Low Pressure Sputtering in a Large Inverted Magnetron Suitable for Film Synthesis." *Rev. Sci. Instr.* 36 (3): 272-82.

[4] Wasa, K., and Hayakawa, S. 1967. "Sputtering in a Crossed Electromagnetic Field." *IEEE Trans. Mater. Packag.* 3: 71-6.

[5] Wasa, K., and Hayakawa, S. 1969. "Low Pressure Sputtering System of the Magnetron Type." *Rev. Sci. Instr.* 40 (5): 693-7.

[6] Corbani, J. F. 1975. "Cathode Sputtering Apparatus." Patent USA 3 878 085 (Priority 5/07/1973, Date of

publication 15/04/1975).

[7] Chapin, J. S. 1979. "Sputtering Process and Apparatus." Patent USA 4 166 018 (application 31/01/1974, Date of publication 28/08/1979).

[8] Chapin, J. S. 1974. "The Planar Magnetron." *Research Development* 25 (1): 37-40.

[9] Kuzmichev, A. I. 2008. "Introduction to the Physics and Technology of Magnetron Sputtering." In *Magnetron sputtering Systems*, Book 1. Kiev: Avers.

[10] Garrett, C. B., and Galif, S. G. 1984. Planar Magnetron Sputtering Device, patent USA, N 4444643, Apr., 24, 1984.

[11] Elphick Christopher, Nyaiesh Alireza. Tunnel Magnetron for Cathode Sputtering. application. British Patent, GB2125440 (A), 1984, 03, 07.

[12] Ramachandran, K. 1983. Ottawa, Canada. Sputtering Apparatus and Method. Patent USA N4498969, Feb., 12.

[13] Berishvili, Z., Skhiladze, G., and Shioshvili, S. 1983. The Arrangement of Ion-Plasma Sputtering in Vacuum. Author's Certificate, № 1160761 (USSR), 1983, Date of publication 8.02.1985.

[14] Berishvili, Z., Gadakhabadze, I., Skhiladze, G., and Shioshvili, S. 1984. The Arrangement of Ion-Plasma Sputtering of Materials in Vacuum. Author's Certificate, № 1244960 (USSR), 1984, Date of publication 15.03.1986.

[15] Berishvili, Z. 2015. Planar Magnetron Sputtering Device. GE P 2016 6512 B, 2015.05.28, Date of publication 2016.07.11 #1329.

[16] Berishvili, Z. 2016. Planar Magnetron Sputtering Device WIPO|PCT, WO 2016/189337 A1, Date of publication № WO 2016/189337 01.12.2016.

[17] Berishvili, Z., Gadakhabadze, I., and Skhiladze, G. 1991. "Improvement of the Methods of Magnetron Sputtering in Vacuum for Production of Thin-film Coatings." *Georgian Engineering News* (ISSN 1512-0287) 4: 108-11.

[18] Vasilev, D., and Moiseev, K. 2015. "Influence of the Planar Cylindrical Target Erosion Area of Magnetron Sputtering on the Uniformity of a Thin-Film Coating, BMSTA." *Seminars IOP, Publishing Journal of Physics: Conference Series* 584: 012012. doi:10.1088/1742-6596/584/1/012012.

[19] Berishvili, Z., Gadakhabadze, I., and Skhiladze G. 1990. "Deposition of Multilayer Coatings Using Magnetron Sputtering Devices." ***J.** Electronic Industry* 4: 29-30.

[20] Berishvili, Z., Jangidze, L., Lezhava, T., Melkadze, R., Peradze, G., and Skhiladze, G. 2004. "Formation of the Bump Contacts for GaAs Pixel Detectors." *Technology and Design in Electronic Equipment* 4: 43-5.

[21] Scholl, R. A. 1997. "Power Systems for Reactive Sputtering of Insulating Films." *Surf/Coat. Technol*. 93: 7-13.

[22] Sellers, J. 1998. "Asymmetric Bipolar Pulsed DC: The Enabling Technology for Reactive PVD." *Surf/Coat. Technol*. 98: 1245-50.

[23] Berishvili, Z. 2016. "High Performance Planar Magnetron Sputtering Apparatus with Rotating Magnetic Field." In *Proceedings of the 4th International Conference "Nanotechnologies" Nano-2016.* pp. 25. October 24-27, 2016, Tbilisi, Georgia.

[24] Schwarz, G., Campbell, M., Goeppert, R., et al. 1999. "X-Ray Imaging Using a Hybrid Photon Counting GaAr Pixel Detector." *Nuclear physics B (Proc. Suppl.)* 78: 491-6.

[25] Schwarz, G., Campbell, M., Goeppert, R., et al. 2001. "Measurements with Si and GaAr Pixel Detectors Bonded to Photon Counting Readout Chips." *Nuclear Instruments and Methods in Physics Research A* 466 (1): 87-94.

[26] Berishvili, Z., Gobronidze, V., Jishiashvili, A., Shiolashvili, Z., Sakhvadze, L., and Skhiladze G. 2005. "The Production of Germanium Quantum Dots in a Film GeO_2." In *Proceedings of the Sixth International Scientific and Practical Conference "Modern Information and Electronic Technologies*, Odessa, Ukraine, p. 242.

[27] Berishvili, Z., Kordzakhia, I., Zardiashvili, D., Abramishvili, G., Avaliani, I., Shalamberidze, D., and Ivanidze, I. 2014. "Modernization of the Vacuum Unit of Type VU-1A to Obtain Multilayered Periodic Optical Coatings." *Nano Studies* 9: 169-76.