Armenian Journal of Physics, 2020, vol. 13, issue 2, pp. 140-148

Minimagnetrons and Their Supply

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Received 21 June 2020

Abstract: Today, magnetron sputtering installations use electrical power in kW or even hundreds of kW. Uniform deposition, as a rule, is achieved by significant removal of the substrate from the sprayed cathode. But as the distance between the sputtered cathode and the substrate increases, the degree of clusterization of the particles increases, i.e. on the surface of the substrate clusters are formed, rather than individual atoms of the sprayed material. This is not always desirable. In addition, difficulties arise in the deposition of multicomponent films. One of the ways to solve this problem is to use partitioned cathodes, when the inserts are made from other sprayed materials into the main cathode material. However, the heterogeneity of the cathode leads to instabilities in the burning of the discharge and to associated defects in the deposited layers. It is more reasonable to use a mosaic of mini-magnetrons, each of which has its own independent power supply, instead of a large-sized magnetron cathode. The article shows the possibility of improving the uniformity of the deposition, including multicomponent films using a system of minimagnetrons. A diagram of the magnetron power source is given.

Keywords: magnetron, sputtering, magnetrons supply, uniformity of sputtering.

1. Introduction

Magnetron ion sputtering systems are modern high-performance atomization systems. The first experiments on magnetron sputtering began in the $30s$ of the $20th$ century. The first patents for magnetron sputtering systems were obtained in the $60s$ of the $20th$ century [1]. One of the first patents for a magnetron atomizer was obtained in the USA in 1988 [2]. This is a relatively new technique on which modern new technologies are based in microelectronics, nanoindustry, plasma chemistry and other areas of science and technology in which thin-film coatings are used.

Today, the magnetron sputtering plants use electric power units and even hundreds of kW. The diameter of the sprayed cathodes is from 5 to $40\,cm$. Naturally, water cooling of both the sprayed cathode and the substrate for sputtering is required. The sputtering rate can reach $15\,nm/s$ or more.

2. Experiments and results

A single magnetron is a structure that is shown in Fig. 1. The principle of operation of the magnetron has been considered in a large number of works [3-8]. A is the magnetron magnet system. Depending on the magnetic field strength, the magnetron is called unbalanced when the magnetic field lines intersect the anode plane and balanced when the magnetic field lines mainly close in the cathode region. B is the sprayed cathode, usually cooled. C is the luminous region of the plasma torus. In the region of the plasma torus, a negative charge prevails [7]. D is the region of the positive column, electrically quasi-neutral. E is the magnetron anode.

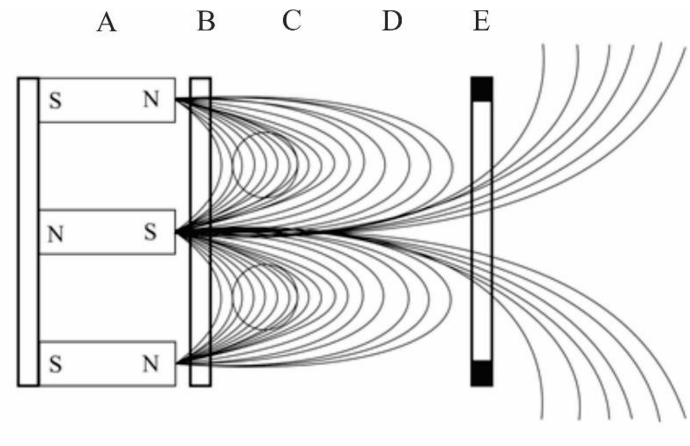


Fig. 1. The scheme of the magnetron for sputtering. *A* is the magnetic system, *B* is the atomized cathode, *C* is the plasma in the form of a ring (torus), *D* is the positive column with magnetic field lines, *E* is the anode.

An important feature of the magnetron discharge is the spraying of the cathode material as a result of bombardment by high-energy ions. During operation of the magnetron, the surface of the anode is contaminated, which requires a periodic shutdown of the spraying process for the cleaning of the anode. A dual magnetron scheme was proposed, in which a separate anode is missed, Fig.2 [9]. Its role is alternately played by the surfaces of two cathodes, combined into a dual structure. Each of the cathodes is contaminated during the time when it works as an anode and is cleaned during the time when it works as a cathode.

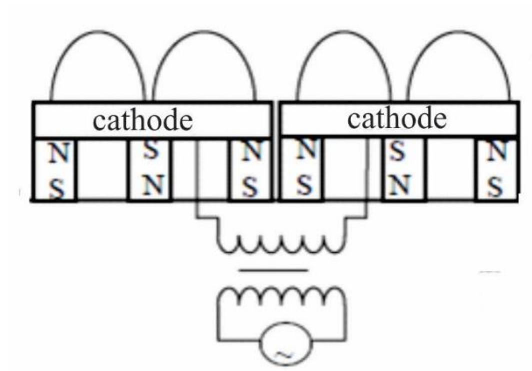


Fig. 2. The dual magnetron system.

All of the above magnetrons give a non-uniform deposition. The cathode sputtering diagram taken from [2] is shown in Fig. 3. The uniformity of sputtering is most often achieved by removing the substrates from the sprayed cathode to such a distance that the entire sputtered area is within the range of visible angles of $\pm 30 - 40^0$ angular degrees. This reduces the sputtering rate and increases the loss of spray material.

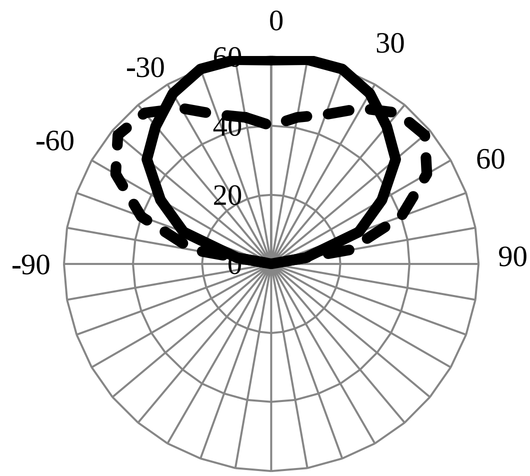


Fig. 3. Sputtering diagram (in polar coordinates). The solid line corresponds to the particle energy of 300 eV, and the dashed one to the energy of 100 eV.

Difficulties arise when sputtering multicomponent films. For this, complex cathodes with inserts from different sprayed materials are often used [9]. But each material has its own sputtering speed and this makes it difficult to choose a spraying mode. Instead of a large magnetron cathode, we propose to use a mosaic of minimagnetrons, each of which has its own independent power supply. In this case, for multi-component sputtering on a substrate, different cathode materials can be used for different minimagnetrons, and the possibility of using different sputtering modes makes it possible to obtain films with controlled stoichiometry. In addition, minimagnetrons are easy to combine into dual - paired and even quadrosystems.

Figure 4 shows the developed single minimagnetron with a cathode diameter smaller than $45\,mm$ and with a plasma torus diameter of $18\,mm$. The ring-shaped anode had a diameter of $50\,mm$. A patent was obtained for the operation of magnetrons in the acoustoplasma mode [10-12].

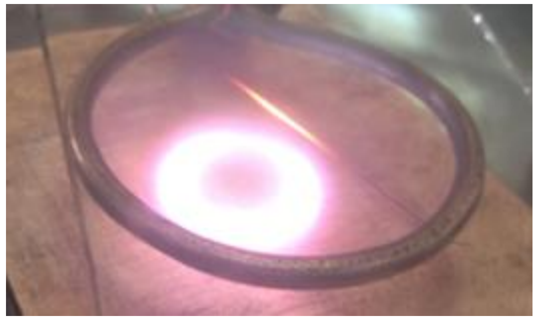


Fig. 4. Single minimagnetron.

Due to the small size of the anode ring, the focusing of ions by the anode ring is strongly manifested. The sputtering diagram of such a magnetron is shown in Fig. 5 [12].

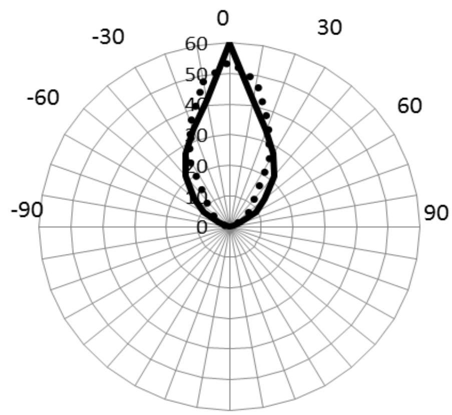


Fig. 5. Sputtering diagram (in polar coordinates). Solid line is for acoustoplasma operation; dashed line is for direct current. The distance between the cathode and the substrate is 4 cm.

As follows from Fig. 5, the sputtering diagram of an individual magnetron has greatly impaired. But the sputtering speed has increased significantly. For a power density applied to the discharge of $90 W/cm^2$ (calculated from the area of the plasma torus), the deposition rate of copper at a distance between the cathode and substrate of $4\,cm$ reached $10-13\,nm/s$. In conventional magnetrons with copper, the deposition rate is $1-2\,nm/s$ [7].

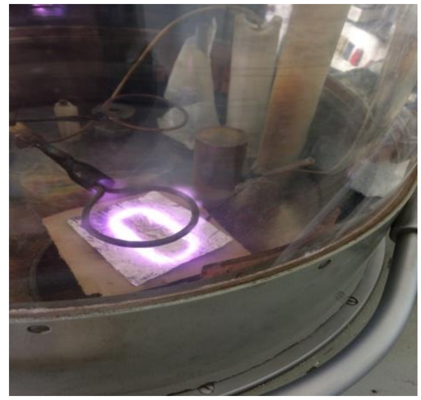
a)  b) 

Fig. 6. Rectangular planar minimagnetron. a) a picture of the magnetic system; b) a luminous plasma ring in a working magnetron.

Figure 6a shows the magnetic system of a rectangular minimagnetron. The external size of a rectangular minimagnetron is $30 \times 60\ mm$. Three cylindrical permanent magnets with a diameter of $10\ mm$ and a height of $10\ mm$ are visible inside, the distance between the magnetic columns is $5-6\ mm$. The outer part of the body is made of steel. Fig. 6b shows a working magnetron, the dimensions of the plasma cord are $20 \times 50\ mm$, and the cord width is $5\ mm$. From fig.6 it can be seen that although the center is not a solid long magnet, but discrete-standing columns, the shape of the plasma cord is the same. This improves the cooling of the magnetic system.

Figure 7 shows an aluminum foil substrate with a deposited layer of copper (Fig. 7a) and (Fig. 7b) the sputtering diagram in rectangular coordinates for a minimagnetron shown in Fig. 4.

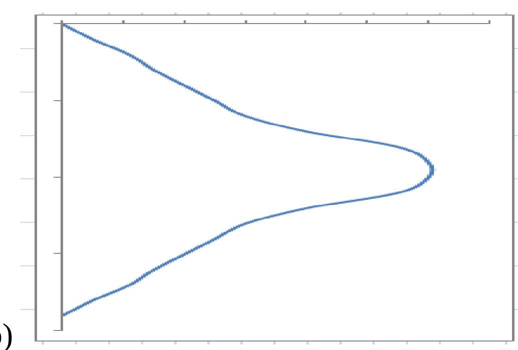
a)  b) 

Fig. 7. Sputtered substrate (a) and sputtering diagram (b) in rectangular coordinates.

As can be seen from Fig. 7, the deposition is nonuniform. But from such minimagnetrons, rectangular or round, one can assemble a block of the required sizes. For a block of 10 minimagnetrons arranged in a line, Fig. 8 shows how the uniformity of sputtering is improved if each individual magnetron has a sputtering pattern shown in Fig. 7b.

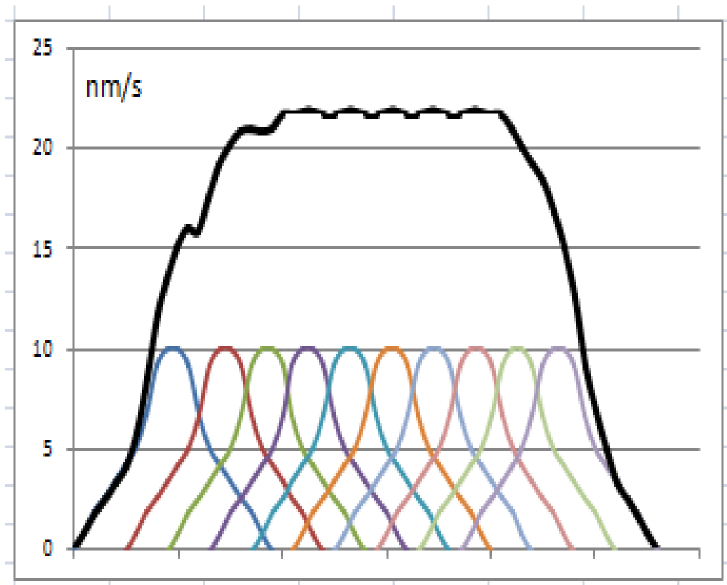


Fig. 8. Uniformity of sputtering for a block of 10 minimagnetrons. The deposition nonuniformity in the middle part can be 1-2%.

In addition, during collective work of minimagnetrons, the deposition rate increases. If for a single minimagnetron the deposition rate was $10\,nm/s$, then for the set of magnetrons the deposition rate was more than $20\,nm/s$. Fig. 9 shows a block of 14 round minimagnetrons, the diameter of each minimagnetron is $12\,mm$. The diameter of the plasma torus of each of the minimagnetrons is $10\,mm$. The dimensions of the entire block are $60\times80\,mm$. The possibilities of interaction of minimagnetrons with each other, the parameters of magnetic systems, and deposition processes were investigated.

Figure 10a shows the regime when all cathodes have a common power supply and a common anode ring. It can be seen that different minimagnetrons produce plasma rings of different intensities, the operating mode is unstable, intense plasma rings can change their location on the block surface. In Fig. 10b, only two neighboring magnetrons work, no power is supplied to the remaining cathodes, even the distance between them is small and the common anode is under potential. A similar regime can be realized in dual magnetrons. In this case, the common anode can be excluded or left to work in the primary ignition mode.

Fig. 9. Block of round minimagnetrons

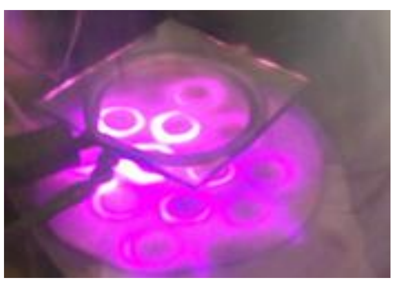
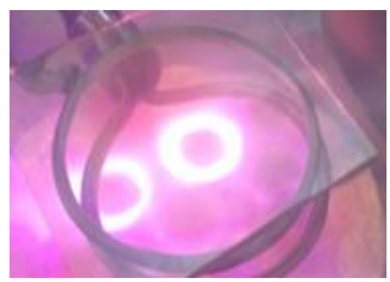
a)  b) 

Fig. 10. Work of assembly of round minimagnetrons. a) all cathodes and anodes have a common power supply, b) power is supplied to two neighboring magnetrons.

The developed power source for acoustoplasma gas-discharge devices is described in [14.]. Figure 11 shows the schematic diagram of a power source. PWM alternating voltage (pulse-width modulated voltage) with amplitude of up to $4\,kV$ from the secondary winding of transformer $T3$ is supplied to a pair of dual magnetrons, as shown in Fig. 2. For a block of minimagnetrons, several secondary windings can be made instead of one, and each pair of minimagnetrons can be connected to different windings.

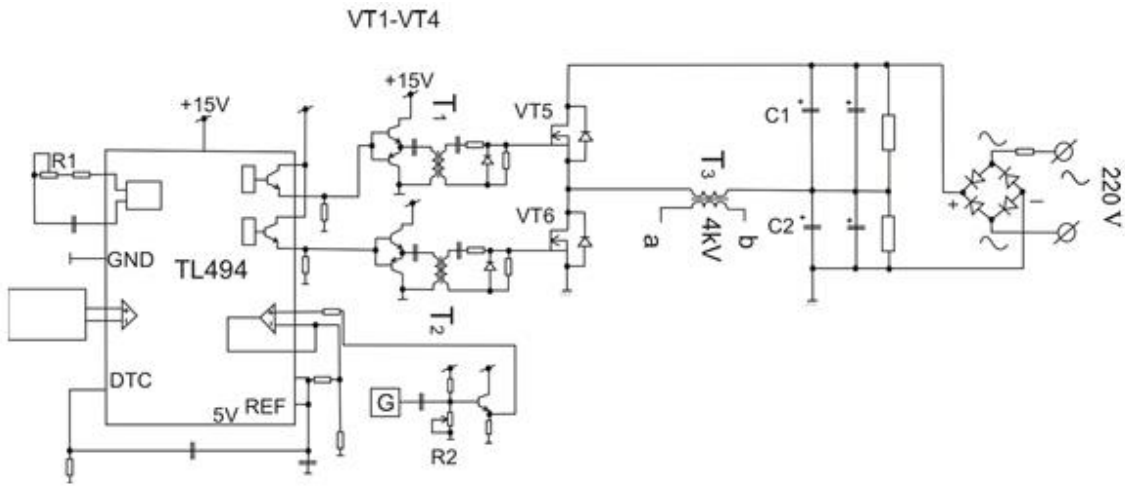


Fig. 11. Diagram of the power supply [14].

3. Conclusion

1. When sputtering, instead of one large magnetron, it is proposed to use a system of minimagnetrons located close to each other**.**
2. Choosing the configuration of the block of minimagnetrons, we can obtain uniform deposition over large areas.
3. The minimagnetron assembly can be located relatively close to the sputtered surface, which is important if undesirable clustering occurs at short distances and if it is necessary to reduce the loss of spray material.
4. Thermal loads on each cathode are reduced, which simplifies the cooling system.
5. The possibility of synthesis and sputtering of multicomponent compositions is simplified. Different cathodes can be made from different materials.

Acknowledgements
The authors are grateful to the Samvel Mkhitaryan and Sarqis Petrosyan for their technical support.

Funding
The paper has been supported from Basic financing of IAPP NAS RA.

Conflict of Interest
The authors declare no conflict of interest.

Author Contributions
The authors equally contributed to all steps of the paper preparation.

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