

Vacuum (gasless) magnetron discharge with a multicomponent sputtering cathode

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It has been shown that the range of cathode-target materials ensuring stable operation of a planar magnetron sputtering system in a vacuum (gasless) mode, without thermal evaporation or sublimation of the cathode material, can be significantly expanded through the use of multi-component targets. These targets include both metals with a relatively high sputtering yield (Cu, Zn, Pb, etc.) and those with a relatively low sputtering yield (Al, Ti, etc.), for which the vacuum mode is not achievable.

Keywords: magnetron sputtering system, self-sputtering, vacuum (gasless) mode, multicomponent targets.

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Magnetron sputtering is one of the most common deposition methods for thin metal coatings. Typical operating pressure range in the magnetron deposition process is $(1-10) \cdot 10^{-3}$ Torr. Unlike traditional magnetron sputtering processes in plasma-forming gas, a vacuum (gasless) magnetron functions at ultimate residual pressure without gas inflow and is supported via self-sputtering mode [1]. In intense cooling conditions, a target cathode surface in the magnetron racetrack region remains relatively cold (below 300 °C) [2], so the main mechanism of metal atom delivery to the ionization zone is an ion sputtering process, rather than sublimation or thermal evaporation, which are inherent in liquid-phase target magnetrons [3].

Gasless magnetron discharge mode has been implemented earlier in a continuous form only on pure metals

(Cu, Ag, Pb) having a relatively high sputtering ratio S_{sputt} (more than 2 atom/ion at $E_i = 600$ eV) [4,5]. Relatively low magnetron discharge voltages (300–600 V) and, accordingly, low S_{sputt} considerably narrow the range of potential materials for a target cathode made of pure metals for vacuum magnetron mode. Multicomponent sputtered targets containing metals with various S_{sputt} can be used as an alternative area for the vacuum magnetron. Previous studies have shown that threshold parameters of magnetron discharge transformation into vacuum mode on such targets can be even lower than on pure copper targets [5]. Multicomponent targets are now widely used in magnetron deposition in „normal“ gas mode (for example, dry lubricants or glucose sensors [6,7]). So-called high entropy alloys have great prospects for use [8]. In some cases such compounds (alloys) have a high proportion of metals with relatively high S_{sputt} , which can potentially support the vacuum magnetron mode [9]. A wide variety of multicomponent targets offers new opportunities for the vacuum magnetron mode and ballistic deposition process in conducting coating deposition techniques.

The purpose of this study is to implement the vacuum magnetron mode on multicomponent targets containing metals with various S_{sputt} (0.5 to 3 atom/ion at $E_i = 600$ eV) and to determine the effect of proportion of these metals on discharge parameters.

The study used a previously developed [10] planar magnetron sputtering system (Figure 1). The magnetron housing was made of stainless steel. Pure metals (Cu, Al, Ni) as well as multicomponent metals: composite (brass, bronze) and mosaic (Cu–Al, Cu–Ti), were used as a target cathode 4. The target diameter was 100 mm. Arch magnetic field in the racetrack region was provided by a set of NdFeB magnets 3 with dimensions of $10 \times 10 \times 10$ mm. The number of magnets varied to change the configuration and adjust the magnetic field strength in the racetrack area. The discharge

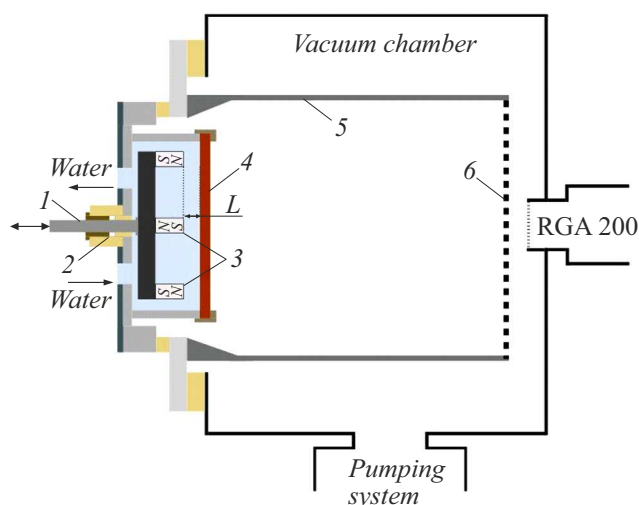


Figure 1. Experimental setup. 1 — holder, 2 — Wilson sealing, 3 — magnetic system, 4 — magnetron target (cathode), 5 — expander (magnetron anode), 6 — grid.

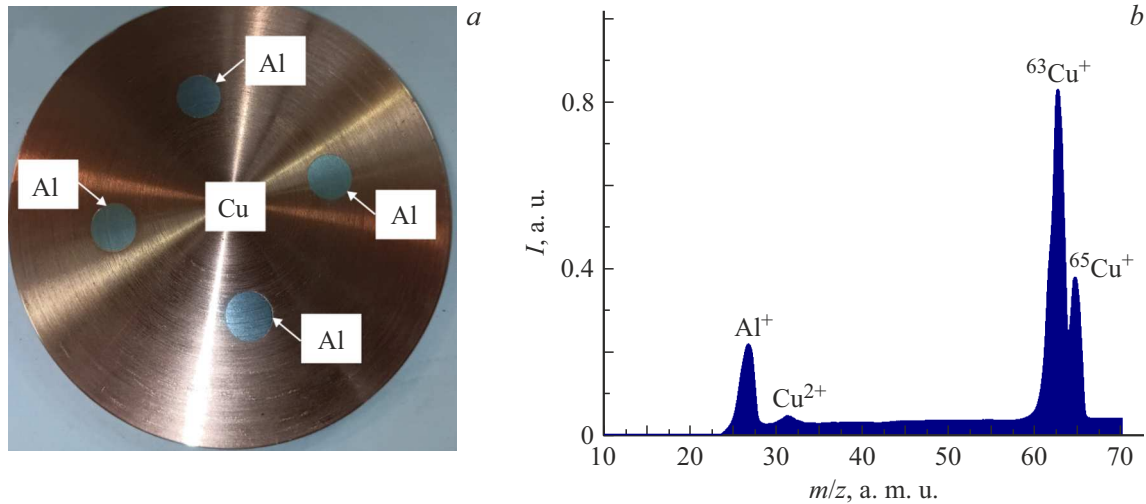


Figure 2. Photograph of a mosaic copper target with aluminum inserts (a) and mass-charge composition of ions (b) in the continuous vacuum magnetron discharge. Magnetron current is 10 A.

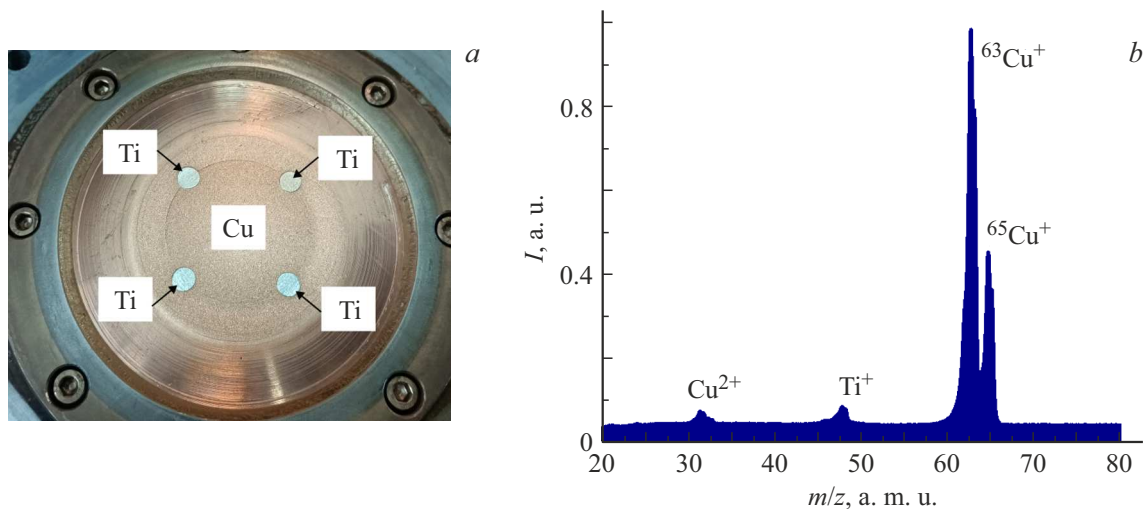


Figure 3. Photograph of a mosaic copper target with titanium inserts (a) and mass-charge composition of ions (b) in the continuous vacuum magnetron discharge. Magnetron current is 10 A.

system was fitted with an axial displacement function of the magnetic system with respect to the magnetron target, which set the distance L from the end of the magnetic system to the rear side of the target.

Direct target cooling with a water flow rate of at least 22 l/min was used for adequate heat removal. Whilst the target surface temperature was about 250–300 °C. Magnetron discharge was first initiated at a plasma-forming gas (argon) pressure of $1 \cdot 10^{-3}$ Torr and voltage between electrodes of about 800–900 V. The specialized APEL-M-20DC-1000SS unit (Applied Electronics, Russia) was used for power supply of magnetron discharge. After discharge ignition, the magnetron current was set at 10 A and argon inflow into the chamber stopped. Vacuum chamber pressure was reduced to about $2 \cdot 10^{-5}$ Torr. The TMN-500 turbomolecular pump was used for vacuum chamber evacuation. Operating pressure was measured in

the immediate vicinity of the magnetron discharge system. For magnetron discharge functioning in vacuum mode, pressure was not higher than $5 \cdot 10^{-5}$ Torr. Analysis of mass charge composition of magnetron discharge plasma ions was performed at a distance of 20 cm from the magnetron target using the RGA-200 (SRS) quadrupole mass spectrometer on the basis of a modified residual gas analyzer, whose measurement procedure had been described in detail earlier in [11].

Fulfillment of a semiempirical expression is a key condition for implementing the gasless self-sputtering mode in the magnetron discharge [12]:

$$S_{\text{sputt}} \alpha \beta > 1, \quad (1)$$

where S_{sputt} is the target sputtering ratio, α is the probability of sputtered metal atom ionization, β is the probability of metal ion return to the cathode.

Target material composition and vacuum magnetron discharge properties

Material	Elemental composition, %	S_{sputt} , atom/ion ($E_i = 600 \text{ eV}$) [14]	S_{Σ} , atom/ion	Discharge voltage, V (at 10 A)	Threshold target current, A
Copper	Cu: 99.9	Cu: 2.4–2.5	—	600–650	7–8
Nickel	Ni: 99.9	Ni: 1.7–1.8	—	700–720	17
Aluminum	Al: 99.9	Al: 1.1–1.2	—	N/A	N/A
Brass	Cu: 60 Zn: 40	Cu: 2.4–2.5 Zn: 3.0–3.2	2.7	580–640	4.8
Bronze	Cu: 85 Zn: 5 Sn: 5 Pb: 5	Cu: 2.4–2.5 Zn: 3.0–3.1 Sn: 2.5–2.7 Pb: 2.5–2.8	2.5	580–640	4.3
Cu–Ti	Cu: 90 Ti: 10	Cu: 2.4–2.5 Ti: 0.6–0.7	2.3	615–630	8.5
Cu–Al	Cu: 80 Al: 20	Cu: 2.4–2.5 Al: 1.1–1.2	2.1	630–646	9

Taking into account that with typical magnetron discharge voltages of 500–600 V for a copper target, S_{sputt} is about 2.3 atom/ion [13], required probabilities of copper atom ionization and ion return to the cathode shall be at least 0.7. Further, for aluminum within the specified ion energy range, S_{sputt} is not higher than 1.2 atom/ion on average, therefore the required values of α and β shall be at least 0.95, which is impractical in the flat-target magnetron discharge considering the low mass and high velocity of aluminum atom transit through the ionization zone. For titanium at S_{sputt} of about 0.6 atom/ion, α and β shall be at least 1.3, which is physically impossible.

Multicomponent targets containing metals both with low and high S_{sputt} used in vacuum mode provide conditions where metal with high S_{sputt} (for example, Cu or Zn) takes on a discharge self-maintaining function and serves as a kind of „donor“ for metals with low S_{sputt} (for example, Al or Ti) included in the target.

When using a multicomponent target consisting of several elements (A , B , etc.), the resultant target sputtering ratio S_{Σ} can be estimated using the following expression

$$S_{\Sigma} = S_{\text{sputt}}^A \omega_A + S_{\text{sputt}}^B \omega_B + \dots, \quad (2)$$

where S_{sputt}^A and S_{sputt}^B are the sputtering ratios of elements A and B ; ω_A and ω_B are the proportions of elements A and B contained in the target, respectively, where $\omega_A + \omega_B + \dots = 1$.

For experimental study of the proposed approach, mosaic targets were made as a model material, where cylindrical inserts 5–10 mm in diameter and 2–3 mm in thickness made of metals with low S_{sputt} (aluminum and titanium) were pressed in a copper target 5 mm in thickness along the racetrack (Figure 2, *a* and 3, *a*). Tight press fitting of

inserts ensured good electrical and thermal contact. The proportion of metal with low S_{sputt} in discharge was adjusted by both the insert diameters and the number of inserts along the racetrack. Visual observations have shown that plasma glow along the racetrack length was less bright in the region of aluminum and titanium inserts, which can be probably explained by a lower concentration of metal atoms in these regions. Nevertheless, the magnetron discharge with aluminum and titanium inserts demonstrated long-term stable functioning in vacuum mode. Studies have shown that proportion of metal ions in the magnetron plasma in vacuum mode on the Cu–Al and Cu–Ti mosaic targets approximately corresponded to the area ratio of each metal in the racetrack zone considering the difference in their S_{sputt} (Figures 2, *b* and 3, *b*). In experiments with a twofold increase in the number of aluminum inserts, the proportion of aluminum ions in plasma almost doubled.

The proposed approach was also studied as applicable to multicomponent targets in the form of ready-made alloys (composites) using brass and bronze. The table shows the composition data for pure and multicomponent targets, and for the effect of metals with high S_{sputt} included in the target on the resultant sputtering ratio of the multicomponent target and threshold parameters of the magnetron vacuum mode. Experimental data analysis shows that the presence of metals with high S_{sputt} („donor“, for example Zn or Pb, in the target (for example, brass or bronze) leads to an increase in the target's resultant S_{sputt} from 2.4 atom/ion for the pure copper target up to 2.7 atom/ion and 2.5 atom/ion for brass and bronze targets, respectively. This ensures almost twofold decrease in the threshold current of the magnetron vacuum mode for brass and bronze targets (4.8 A and 4.3 A, respectively) compared with the threshold current of the pure copper target (7–8 A).

The obtained experimental results show that the conducting coating deposition capabilities and processes in vacuum (gasless) mode of the magnetron sputtering system can be considerably expanded through the use of multicomponent target cathodes consisting of metals with both relatively high and relatively low sputtering ratio. A key condition in this case is the presence of a „donor“ metal with a high sputtering ratio in the target in the number sufficient to provide stable functioning of a magnetron vacuum mode.

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Conflict of interest

The authors declare no conflict of interest.

References

- [1] W. Posadowski, Surf. Coat. Technol., **49** (1-3), 290 (1991). DOI: 10.1016/0257-8972(91)90071-4
- [2] M.V. Shandrikov, M.I. Azhgikhin, E.M. Oks, A.A. Cherkasov, Russ. Phys. J., **68** (6), 933 (2025). DOI: 10.1007/s11182-025-03512-1
- [3] A.V. Tumarkin, A.V. Kaziev, M.M. Kharkov, D.V. Kolodko, I.V. Ilychev, V.G. Khodachenko, Surf. Coat. Technol., **293**, 42 (2016). DOI: 10.1016/j.surfcoat.2015.12.070
- [4] W.M. Posadowski, Vacuum, **46** (8-10), 1017 (1995). DOI: 10.1016/0042-207X(95)00096-8
- [5] S. Kadlec, J. Musil, Vacuum, **47** (3), 307 (1996). DOI: 10.1016/0042-207X(96)80013-3
- [6] M. Cao, L. Zhao, L. Wu, W. Wang, Coatings, **8** (4), 134 (2018). DOI: 10.3390/coatings8040134
- [7] Y. Yin, T. Zhang, L. Feng, J. Ran, C. Ma, Y. Tan, B. Yang, RSC Adv., **13** (21), 14641 (2023). DOI: 10.1039/D3RA02076B
- [8] D.B. Miracle, O.N. Senkov, Acta Mater., **122**, 448 (2017). DOI: 10.1016/j.actamat.2016.08.081
- [9] M. Sadeghi, B. Niroumand, Intermetallics, **151**, 107658 (2022). DOI: 10.1016/j.intermet.2022.107658
- [10] M.V. Shandrikov, E.M. Oks, V.O. Oskirko, A.A. Cherkasov, Pisma v ZhTF, **49** (22), 19 (2023) (in Russian). DOI: 10.61011/PJTF.2023.22.56594.19716 [M.V. Shandrikov, E.M. Oks, V.O. Oskirko, A.A. Cherkasov, Tech. Phys. Lett., **49** (11), 55 (2023). DOI: 10.61011/TPL.2023.11.57201.19716].
- [11] M.V. Shandrikov, A.A. Cherkasov, E.M. Oks, A.V. Vizir, AIP Adv., **12** (2), 025017 (2022). DOI: 10.1063/5.0081234
- [12] A. Anders, J. Andersson, in *2008 23rd Int. Symp. on discharges and electrical insulation in vacuum* (IEEE, 2008), p. 561–566. DOI: 10.1109/DEIV.2008.4676856
- [13] W.H. Hayward, A.R. Wolter, J. Appl. Phys., **40** (7), 2911 (1969). DOI: 10.1063/1.1658100
- [14] *Sputtering by particle bombardment: experiments and computer calculations from threshold to MeV energies*, ed. by R. Behrisch, W. Eckstein (Springer, Berlin–Heidelberg, 2007), p. 110.

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