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Vacuum arc deposition as a complementary technology to laser processing

N.F. Vershinin [a,b], V.G. Glebovsky [a], B.B. Straumal [a,c,*], W. Gust [c], H. Brongersma [d]

[a] *Institute of Solid State Physics, Chernogolovka, Moscow District 142432, Russia*
[b] *SONG Ltd., P.O. Box 98, Chernogolovka, Moscow District 142432, Russia*
[c] *MPI Metallforschung and Institut für Metallkunde, Seestr. 75, D-70174 Stuttgart, Germany*
[d] *Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands*

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Abstract

Vacuum arc deposition unifies the advantages of laser ablation and magnetron sputtering. The evaporation of the target in the arc discharge permits to deposit the refractory materials with a high rate. The evaporation products are highly ionized and the possibility exists to control the discharge with a magnetic field. The deposition rate, R_d, of Mo films produced by vacuum arc deposition on Cu and silica glass substrates has been studied. The target of purified Mo has been made by high-vacuum electron beam melting. R_d depends critically on the angle between the substrate and the cathode surfaces being maximal when they are parallel. The adhesion of the Mo coating to Cu is much higher than to silica glass substrate. R_d as high as 15 nm/s has been reached. R_d increases with increasing deposition power. It decreases with increasing distance from the cathode slower than in the case of magnetron sputtering. The microparticles forming by the vacuum arc evaporation incorporate in the layer during the deposition procedure increasing the deposition rate.

1. Introduction

Last decade the vacuum arc deposition attracts more attention as an effective technology for the deposition of high-quality films of metals, alloys, carbon (amorphous diamond), and compounds [1,2]. The pioneer studies of the vacuum arc discharge were conducted in the 60s [3,4]. Later, applications of the vacuum arc deposition were developed [5–7]. Vacuum arc deposition unifies the advantages of both laser ablation and magnetron sputtering. On the one hand, in the vacuum arc discharge the ionized species are produced, as also in the case of magnetron discharge [8]. It makes possible the control of their trajectories and, therefore, the deposition process with the aid of magnetic and electrical fields. On the other hand, the vacuum arc includes the melting of the target material in the arc spot, as also in the case of laser ablation. It makes possible, for example, the deposition of complex materials with an excellent transfer of the stoichiometry from the target to the film [9,10]. The deposition of Mo films is technologically important due to their low diffusion permeability. The deposition rate of Mo in the

* Corresponding author. Tel.: +49-711-1211276; fax: +49-711-1211280; e-mail: straumal@vaxww1.mpi-stuttgart.mpg.de.

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case of magnetron sputtering is rather low because of its low sputter yield [11]. Therefore, Mo has been chosen for the experiments of the vacuum arc deposition.

2. Experimental

Mo coatings have been deposited onto polished copper and silica glass substrates in a vacuum arc apparatus described elsewhere [12]. The pumping system of the apparatus consists of a Balzers turbomolecular pump with a capacity of 1500 ℓ/s and two rotary pumps with a total capacity of 40 ℓ/s. The pressure during deposition is 8×10^{-4} Pa. The vacuum chamber has the form of a horizontal cylinder of 700 mm diameter and 500 mm length. On the end of this cylinder the vacuum arc apparatus with the magnetic system for spot stabilization and the Mo cathode are placed. The cathode of diameter $D = 60$ mm was made from 99.95% Mo. It was prepared by high-vacuum electron-beam multiple melting in specially designed water-cooled copper moulds [13]. The facilities for magnetic filtering of the macroparticles were not used in this study. The polished Cu (roughness before coating $R_a = 20$ nm) and silica glass ($R_a = 10$ nm) substrates were placed in different distances L from the surface of the cathode ($L = 50$, 175, 300, and 425 mm). At each distance the substrates were positioned parallel ($\theta = 0°$) and perpendicular ($\theta = 90°$) to the plasma flow coming axially from the cathode (θ is the angle between the direction of plasma flow and the surface of substrate). The vacuum arc source voltage was constant $U = 31$ V, and the discharge current I was changed ($I = 80$, 100, 140, and 180 A). The strength of the stabilizing magnetic field on the cathode surface was 60 to 70 G. No bias has been applied to the substrates. The coating time t was changed ($t = 5$, 10, 20, and 40 min). In order to avoid an overheating of the substrates the coating process was interrupted (in vacuum) every 2.5 min for 2.5 to 3 min. The thickness of the coatings d was measured with the aid of a profilometer and an optical microscope. With the aid of a polystep profilometer the height of a step was measured between the coated and protected halves of the substrate with an accuracy of 5 nm. The thickness of coatings with $d > 1$ μm was additionally measured with the aid of a Zeiss Axiophot optical microscope. The deposition rate was determined as mean value for four deposition times. The ratio S_d/S_t of the substrate area S_d, where the Mo coating was spontaneously delaminated to the total substrate area S_t was also determined for all substrates studied by quantitative metallography.

3. Results and discussion

In Fig. 1b the dependencies of the deposition rate R_d are shown on the discharge power P for different L/D ratios for substrates oriented parallel to the plasma flow (and perpendicular to the surface of cathode), L being the distance between the substrate and the cathode and D the cathode diameter. The literature values for the Mo magnetron sputter deposition are also shown in Fig. 1a for a substrate which is oriented parallel to surface of the rectangular target with the dimensions 13×38 cm and moves with a velocity $v = 8$ cm/min at a distance $L = 6$ cm from the target [14]. Therefore, the L/D ratio for

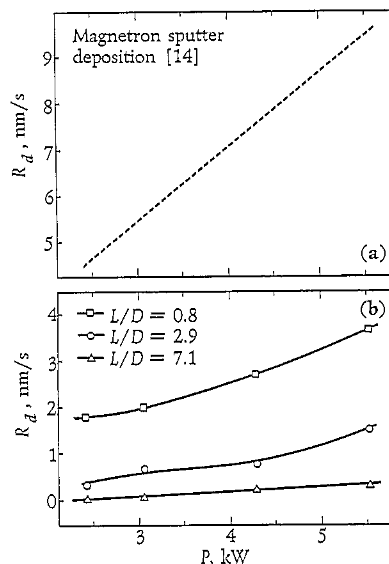

Fig. 1. Dependencies of the deposition rate R_d on the discharge power P. (a) Magnetron sputter deposition, $L = 60$ mm, target 130×380 mm, $\theta = 90°$ [14]. (b) Vacuum arc deposition for different L/D values, $\theta = 0°$.

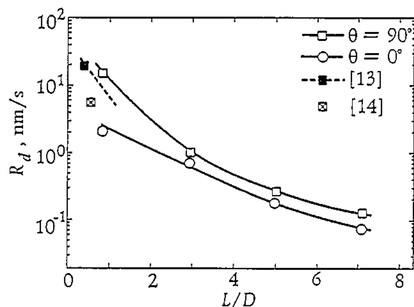

Fig. 2. Dependencies of the deposition rate R_d on the L/D ratio for substrates oriented parallel and normal to the plasma flow (L is the distance between the substrate and the cathode, and D is the cathode diameter) for $P = 3.1$ kW.

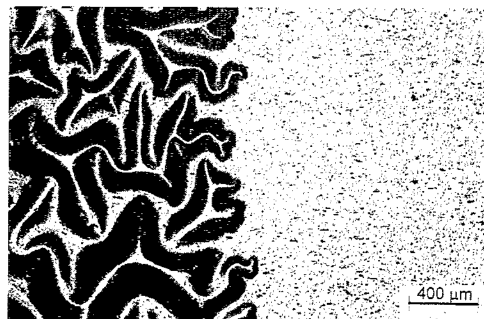

Fig. 3. Optical micrograph of the microstructure of the Mo coating on silica glass ($P = 4.3$ kW, $L = 50$ mm, $t = 5$ min, $\theta = 0°$, $d = 0.5$ μm). A part of the coating delaminates spontaneously from the substrate (see left side of the micrograph).

this case can be estimated as lying between 0.16 and 0.46. R_d for vacuum arc deposition increases monotonically with increasing discharge power. Close to the cathode this increase is most pronounced. But R_d for vacuum arc deposition does not depend on the discharge power so strongly as in the case of magnetron sputter deposition even at $L/D = 0.8$.

In Fig. 2 the R_d dependencies are shown on the L/D ratio for substrates oriented parallel and normal to the plasma flow coming from the cathode for $P = 3.1$ kW. The literature values for the Mo magnetron sputter deposition are also shown for the same discharge power and comparable L/D ratios [11,14]. The broken line shows the slope of the $R_d(L/D)$ dependence for the magnetron sputter deposition taken from [11]. Normally, only the R_d values for $L/D < 1$ can be found in the literature for the magnetron sputter deposition, because reasonable deposition rates can be reached only if the substrates are positioned close to the target. If the distance L exceeds the diameter of the magnetic ring behind the target the deposition rate decreases with increasing L even faster as it is shown in Fig. 2. It is obvious that R_d for vacuum arc deposition decreases with increasing L much slower than in the case of magnetron sputter deposition. It can be also clearly seen that the vacuum arc deposition permits to obtain R_d values which are higher than R_d values reached with the aid of magnetron sputter deposition at the same values of P, L/D and θ. The R_d values on the substrates perpendicular to the plasma flow ($\theta = 90°$) are higher than for $\theta = 0°$. But this difference decreases with increasing L/D. A slow decrease of R_d with increasing L/D and comparable values for normal and tangential incidence make easy the coating of non-planar and three-dimensional parts with the aid of vacuum arc deposition.

The micrograph in Fig. 3 shows the microstructure of Mo coating on silica glass ($d = 0.5$ μm). It is clearly seen that a part of the coating (in the left side of the figure) delaminates spontaneously from the substrate. The delamination of the coating can be used as a semi-quantitative measure of the coating adhesion to the substrate. For this purpose, the ratio

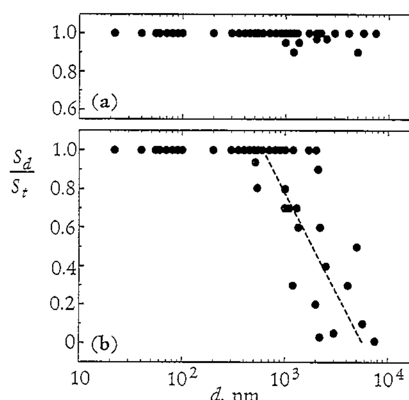

Fig. 4. Dependencies of the portion of the substrate area S_d/S_t where the Mo coating was spontaneously delaminated on the coating thickness d for Cu substrate (a) and for silica glass substrate (b).

S_d/S_t of the substrate area S_d, where the Mo coating was spontaneously delaminated, to the total substrate area S_t was determined for all substrates studied. In Fig. 4 the dependencies of S_d/S_t on the coating thickness d for Cu and silica glass substrates are shown. Practically no delamination was observed on the Cu substrates. Only a very minor delamination was present for some thick coatings close to the edge of the substrate. The adhesion of Mo coatings to the silica glass is poorer. At d about 0.5 to 1.0 μm a spontaneous delamination starts. The internal stresses in the coating begin to exceed the adhesion force. For $d > 5$ μm the coatings are practically totally delaminated. Only the thinner parts of the films are still in the contact with the substrate. Therefore, the Mo films can be easily delaminated from the silica glass substrate after deposition in the absence of a bias voltage. This feature can be in principle used for manufacturing of thin Mo foils. For this purpose, another substrates instead of silica glass can be used with a lower adhesion, like for example fluoroplast. In the case of lower adhesion a spontaneous delamination can be reached for films with a thickness even lower than 1 μm.

The most important similarity between laser ablation and vacuum arc deposition is that the material evaporates locally from the surface of target. In particular, this feature allows rather accurate transfer of the composition of multicomponent target to the depositing film. Another similarity is the formation of microparticles during the vacuum arc deposition. These particles can be clearly seen in Fig. 3. The splashing effect in the laser ablation [15] also involves the formation of microparticles between 0.1 and 10 μm in size. Both mean size of particles d and the fractional coverage depend on the P, L/D and θ [16]. The values of d and $\Sigma S/S_t$ decrease with increasing L/D faster than the deposition rate. Already at $L/D > 1$ the values of $\Sigma S/S_t$ become rather low (about 10^{-3} to 10^{-4}), and the coatings are almost free of particles. The microparticles incorporate into the layer during the deposition procedure [16]. This feature plays an important role in the increase of R_d close to the target. Important difference to laser ablation is that in case of vacuum arc deposition practically all individual atoms evaporated from the target are ionized. The ratio of multiply charged ions is high especially in case of Mo [17]. It allows one to filter the ions from the microparticles.

4. Conclusions

Vacuum arc deposition unifies the advantages of laser ablation and magnetron sputtering. The dependencies of the deposition rate for vacuum arc deposition of Mo on the discharge power and distance from the cathode have been studied. A deposition rate as high as 15 μm/min is reached. It is higher than deposition rate which can be obtained by magnetron sputter deposition at comparable values of the discharge power and distance from the cathode. The deposition rate in the case of vacuum arc deposition decreases with increasing distance from the cathode much slower than in case of magnetron sputter deposition. The deposition rates for the substrates parallel and perpendicular to the plasma flow are comparable. It makes easy the coating of non-planar and three-dimensional parts. It is also shown that after deposition in the absence of a bias voltage the Mo films can be easily delaminated from the silica glass substrate. It creates the possibility to manufacture thin Mo foils.

Acknowledgements

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