Magnetron Discharge in the Diode with a Liquid-Metal Target

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Abstract – The operation of a high power density magnetron source in standard and self-sputtering modes are discussed. To understand main properties of the magnetron in self-sputtering mode the light emissive spectra was received and investigated for various conditions of magnetron operation. It is shown that the magnetron based on liquid-metal sputtering process has high rate deposition and able to operate under self-sputtering mode (without operating gas).

1. Introduction

To-day magnetron thin film coatings are widely adopted in a lot of science and engineering branches [1]. The further development of this process connected with increasing of rate deposition, improving of adhesive properties and uniformity of thickness, injurious impurity reduction etc.

In our opinion, one of the most perspective technologies of the coating production is the magnetron sputtering of metal from a liquid phase target. It allows combining advantages of two thin film deposition methods as vacuum evaporation and ion sputtering. The films, created by means of the first way are featured by high deposition rate and purity, but have poor adhesive. The magnetron sputtering process is more convenient, allows creating of chemical compounds and ensures the more small fractionating during multicomponent target sputtering [2].

This method can allow enhancing the sputtering process efficiency and improving properties of the thin film.

2. Magnetron with a Liquid-Metal Target

It is known [3] that for DC magnetron sputtering system (MSS) the sufficient part of input power (up to 80%) is transformed to heat in the target, which should be cooled. This makes realization of sputtering process on liquid phase target not complicated. It is enough to put the target material into the hard-melting and heat-insulated crucible. In this case the ion bombardment of target surface its temperature is risen up to melting. The sputtering efficiency of melting surface in comparison with solid is greater, because the binding energy of atoms located on the surface is smaller. Moreover, the evaporation process starts at melt temperature rising. So the plasma energy that absorbed by target and lost through the cooling system can be used for intensification of evaporating process.

At sufficient energy density there is opportunity to transform the magnetron discharge in a regime when evaporated atoms of target are used as a working gas of sputtering process. That allows decreasing the film contamination by residual gases.

For investigation of this process we had created the magnetron system [4]. The drawing is presented in Fig. 1. Target (*1*) is put into the hard-melting crucible (*2*), which is heat-insulated from magnetron body by means of ceramic elements (*3*) and is encircled by pole pieces of central (*4*) and external (*5*) magnetic circuit. Magnetic system (*6*) includes permanent magnets, cooled by flowing water. The ring (*7*) is made of nonmagnetic material.

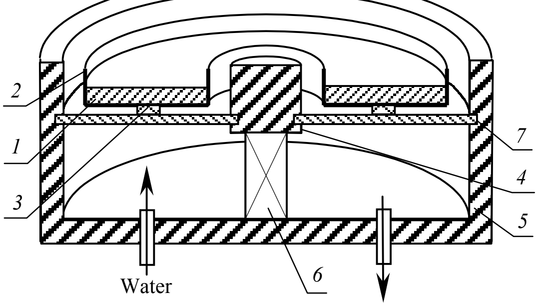

Fig. 1. The construction of magnetron diode: *1* – target material; *2* –crucible; *3* – ceramic units; *4* –central magnetic circuit; *5* – magnetron body; *6* – permanent magnets; *7* – nonmagnetic ring

3. Experimental Results

Purpose of the work was to investigate main electrophysical and technological properties of MSS with a liquid-metal target. Firstly we researched the process of magnetron discharge transforming from a solid to liquid phase sputtering mode. We measured changes of the crucible temperature, voltage and magnetron discharge current under target heating. Number of metals, such as lead, aluminum, tin, copper had been considered. The crucible temperature was measured by means of thermocouple transducers. Obtained dependences for aluminum target are shown in Figs. 2, 3 and 4.

Gradual current decreasing takes place after discharge initiation (see Fig. 2). This is a result of oxide film presence on the target surface and raising of the electron emission current from the target surface. (Molter's effect [5]). The process of clean metal surface sputtering is started after oxide film has been removed. The discharge current is stabilized (low plateau in Fig. 2) up to beginning of target melting, approximately corresponded to point of time $t \approx 300$ s.

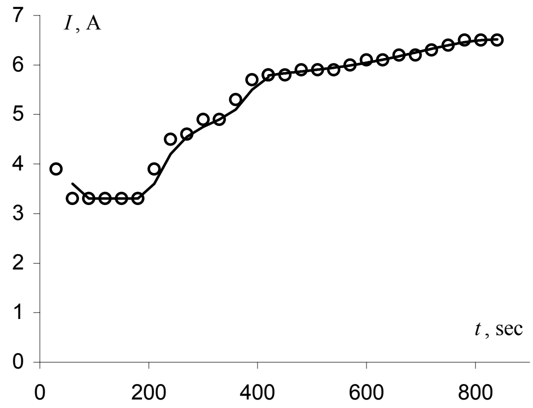

Fig. 2. The time dependence relatively discharge current

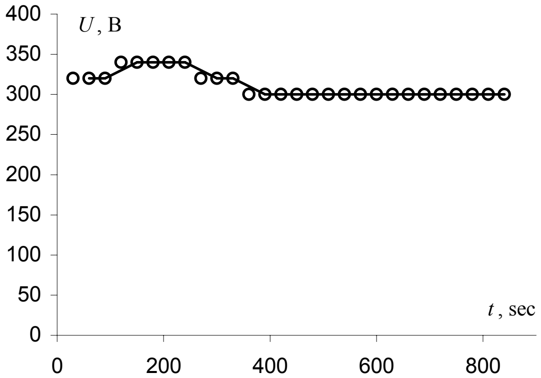

Fig. 3. The time dependence relatively discharge voltage

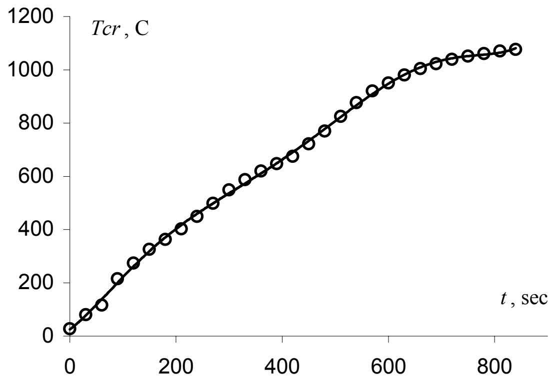

Fig. 4. The time dependence relatively crucible temperature

Melting process of the target surface starts from area of maximum plasma localization and then propagates on remaining part of this. In point of time $t \approx 400$ s related to completely melted target. This is confirmed by the crucible temperature curve pictured in Fig. 4. From this dependence also follows, that interphase transform of material connected with slowed increasing of crucible temperature as result of the heat consumption for melting process. The further insignificant increasing of discharge current (in Fig. 2) is determined by the thermal electron emission rising from a melt.

Limitation of supplier power is influence on the curve of Fig. 3. The current rise results of voltage reducing and vice versa.

The steady-state conditions of the device (balance of current, voltage and sputtering material temperature with power input) are of great interest from viewpoint of technological capabilities of MSS with liquid-metal target. We have investigated current dependences of crucible temperature, voltage and deposition rate to study these operating modes. Results of the research with aluminum target application are shown in Figs. 5, 6 and 7.

The argon pressure in vacuum chamber was equal to 0.09 Pa. Each separately taken point of dependences had been measured in constant current mode after steady-state conditions established. The deposition rate was measured by the piezoelectric microweighing method.

The each cited curve can be conditionally broken in two parts, related the sputtering process of solid and liquid target. Interphase transaction took place under current 5 A. Under this current the target material in the crucible completely melts during 2÷3 min.

The target melting process always is accompanied by current growth as a result of additional ionization of metal vapor and increasing of thermal emission current from the melt. In our case the current is stabilized by power supply. Therefore the discontinuously changed voltage takes place (see Fig. 6). Further current growth results of small increasing of crucible temperature and discharge voltage. Then these parameters are reaching stable position.

The current dependence of film deposition rate is similarly (see Fig. 7). At start time point, when target is in solid state and since the melting (up to $I = 6$ A), the insignificant rise of deposition rate is observed. That is probably connected with starting of target evaporation. Then parts of deposition rate abrupt rise and further its saturation take place.

Reaching defined current after which dependences pictured in Figs. 5, 6 and 7 starts slow changing (for copper it corresponds to $I = 8$ A) the self-sputtering process is initiated. After that external argon supplying in working chamber can be stopped. The melt temperature in this mode is not less than 1250 °C (see Fig. 5). This corresponds to saturated vapor pressure of lead 0.13 Pa. This is comparable to MSS operating pressure with solid target.

Self-sputtering mode is a very interesting as the form of discharge. It not only ensures the high deposition rate and film purity but opens up new possibilities to making and applying of low-temperature metal plasma in different field of science and engineering. However, the effects of metal ions or neutrals on the plasma formation often are overlooked. The metals are able significantly change the ionization efficiency of the plasma and as result to effect on the sputtering process.

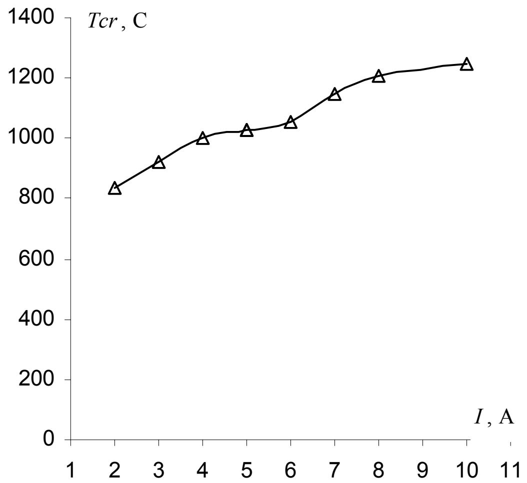

Fig. 5. Current dependences of crucible temperature

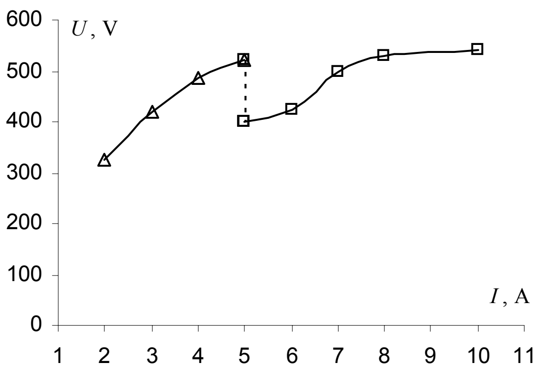

Fig. 6. Current dependence of discharge voltage

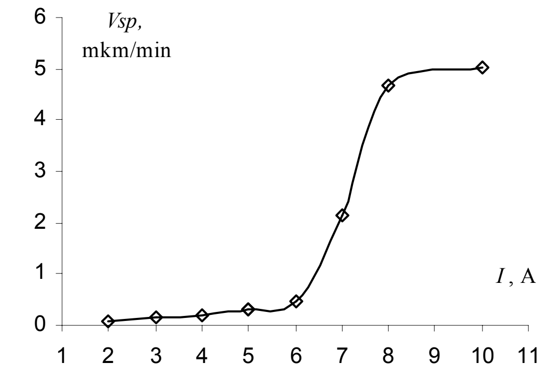

Fig. 7. The film rate depositing dependence of the current

We studied the plasma of magnetron discharge in operating chamber both at the argon presence as well as in a self-sustained sputtering mode. For that light emission spectra of magnetron plasma [6] have been investigated. In this work monochromator MUM-1 and photomultiplier tube FEU-85 was used. A lead was used as target material. The spectra were taken at 350÷500 nm wavelength interval. The collected spectral lines are presented in Table 1.

Figure 8 shows experimental spectrum of discharge plasma together with magnetron operating parameters (discharge current, voltage, gas pressure and crucible temperature). The sign “+” in brackets shows to spectral line belonging to ion and sign “0” – to neutral. Two spectrums at down part of Fig. 8 have been taken under crucible temperature 700 °C and varied argon pressure. The top spectrum related to the self-sputtering mode, which is possible at T_{cr} > 850 °C. All spectrums have been measured at the stabile discharge current (1.2 A).

Table 1. Selected spectral lines of argon and lead [7]

L, nm	Element	*L*, nm	Element
357.3	Pb(0)	416.8	Pb(0)
364.0	Pb(0)	419.8	Ar(0)
367.2	Pb(0)	424.5	Pb(0)
368.3	Pb(0)	425.9	Ar(0)
373,0	Ar(+)	427.3	Pb(0)
374,0	Pb(0)	433.4	Ar(0)
383.5	Ar(0)	438.6	Pb(+)
385.4	Pb(+)	442.6	Ar(+)
402.0	Pb(0)	451.0	Ar(0)
405.8	Pb(0)	476.1	Pb(+)
415.3	Pb(+)	500.5	Pb(0)

Figure 8 shows experimental spectrum of discharge plasma together with magnetron operating parameters (discharge current, voltage, gas pressure and crucible temperature). The sign “+” in brackets shows to spectral line belonging to ion and sign “0” – to neutral. Two spectrums at down part of Fig. 8 have been taken under crucible temperature 700 °C and varied argon pressure. The top spectrum related to the self-sputtering mode, which is possible at T_{cr} > 850 °C. All spectrums have been measured at the stabile discharge current (1.2 A).

While the magnetron discharge is sustained by argon, the ion and neutral lines of argon and lead are very apparent. Their intensity is not changed with gas pressure reducing in spite of the voltage is strongly risen. It is detected that spectral lines intensity more active depends on the discharge current but not on the voltage. In our opinion that is a result of the dependence of atom excitation and ionization mainly on Hall current, related with discharge current. At current increases the ion and excitation atom density in the plasma increases. In a self-sputtering mode (at the top of Fig. 8) all argon lines observed originally are absent. It is evidence of self-sustained discharge form.

Then we recorded magnetron discharge plasma spectrum under crucible temperature 860 °C and argon pressure up to 0.5 Pa in self-sputtering mode. Results tuned out the same as the top specter in Fig. 8 (self-sputtering mode), when argon lines are practically lacking.

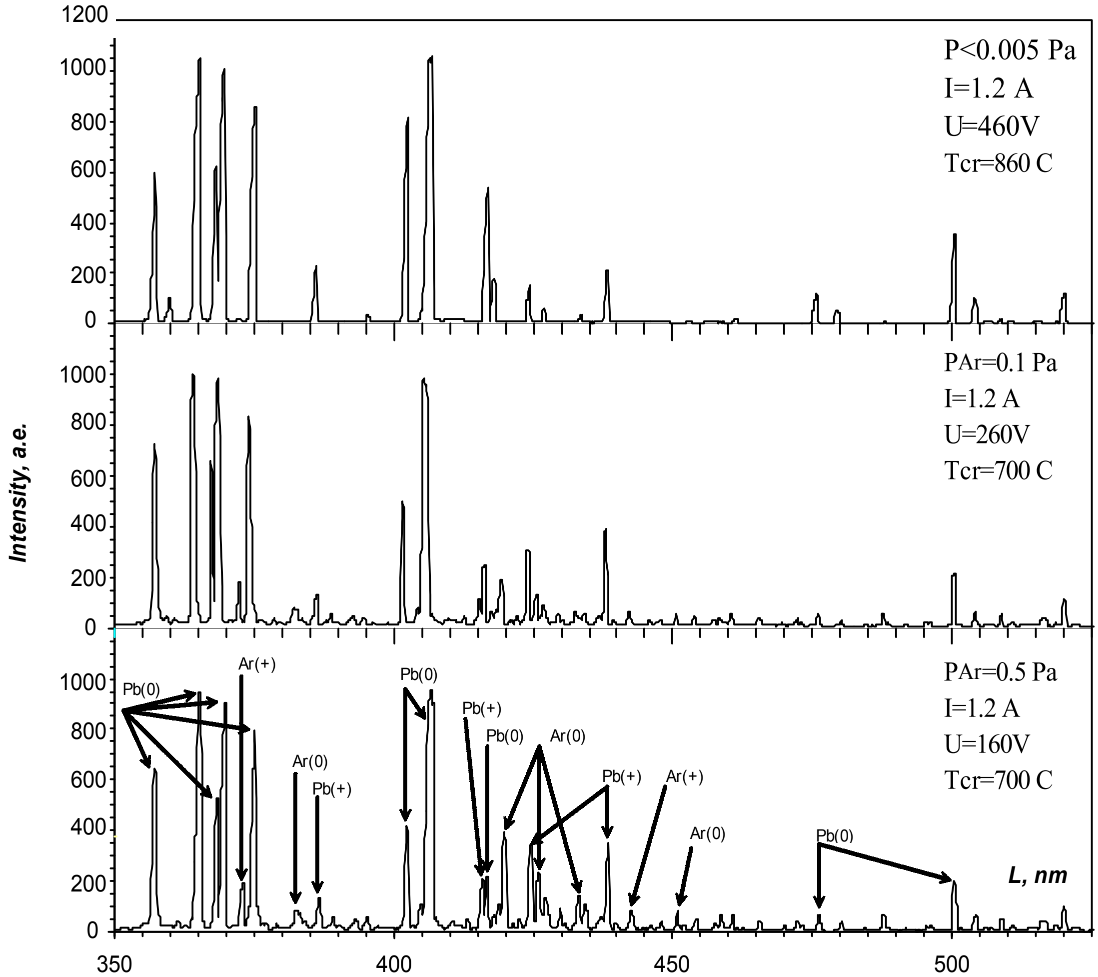

Fig. 8. Light emission spectrum of magnetron discharge plasma with liquid led target under three different operating pressure

Taking into consideration that argon ionization potential is higher than this one for sputtering metal, we can conclude the following. Rare gas presence is very important for the discharge initiation and for operating under low power consumption. For high power and high pressure saturated vapor of sputtering material mode, the cathode potential redistribution takes place. Thus, the Hall electrons in own cycloid moving do not get enough energy for efficiently exciting and ionizing of argon atoms. The sputtering particles have important role within a gas discharge, because their potential energy is less than argon one and their ionization cross-section is higher too.

Therefore, the target sputtering process at the power more than above indicated critical level mainly carried out by means of own particles.

4. Conclusion

The results of our research confirm the high availability of magnetron metal sputtering from a liquid phase for thin film technologies. In particular, the significant increasing of deposition rate in comparison with solid target sputtering is observed. There is ability to exclude the impurity atoms of working gas from the deposited film structure.

It is shown that sputtering target atoms after ionization in discharge area have substantial contribution in a plasma formation process.

References

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