

# High-power sputtering employed for film deposition

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**Abstract.** The features of high-power magnetron sputtering employed for the films’ deposition are reviewed. The main physical phenomena accompanying high-power sputtering including ion-electron emission, gas rarefaction, ionization of sputtered atoms, self-sputtering, ion sound waves and the impact of the target heating are described.

Magnetron sputtering (MS) is a well-known technology for the deposition of films of various material used in a wide range of applications. Two areas of performance improvement are being developed in the MS technology. The first one is based on an increase in the degree of ionization of the sputtered flux [1–7], the second one is based on an increase in the temperature of the target surface up to the melting temperature [8–13]. The methods that ensure a high degree of ionization of sputtered atoms are called ionized physical vapor deposition (IPVD) [1]. A very high density of charged particles, which increases with increasing power density on the target, is common to all IPVD methods. But the increase of power density is limited by the melting temperature of the target material.

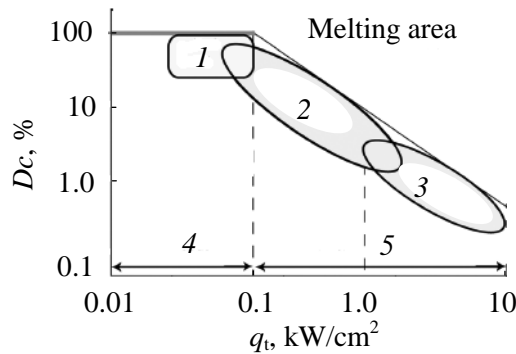
Initially, the processes of the IPVD-type magnetron sputtering were based on the use of a conventional direct current magnetron with an additional HF generator that induces inductively coupled plasma in a vacuum chamber. In other cases, IPVD was achieved by applying a single-polarity pulse of high power, low frequency and low pulse ratio. This method was called high power pulsed magnetron sputtering (HPPMS) [14]. There are several options of HPPMS technology. A very short (tens of microseconds) pulses with very large amplitudes (more than 600 V) at a frequency of more than 50 Hz are applied to the target in high power impulse magnetron sputtering (HiPIMS). In order to distinguish this technique from other impulse magnetron processes, it is suggested in [15] that the peak power exceeds the time average by 2 orders in HiPIMS methods.

Sometimes a DC power supply is used to keep the magnetron sputtering at direct current (PMSdc – pulse magnetron sputtering direct current) with superimposition of powerful pulses with high ratio. This method is called HiPIMS with pre-ionization. Other approaches include pulse modulation in such a way that impulses (several hundred microseconds) are delivered to the target with a moderate power level (typical for DCMS) at the initial stage. Then a high power pulse is followed (from several hundred microseconds time interval to millisecond). This method is called modulated pulse power (MPP) [1].

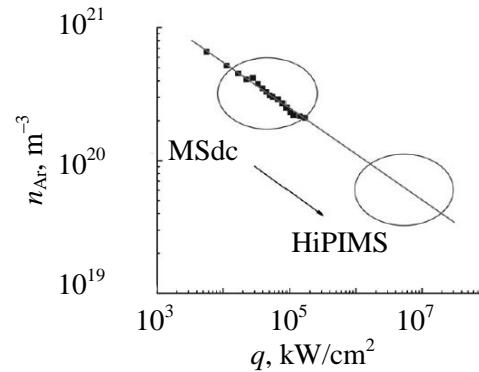
Figure 1 shows the plane for the platinum target in the coordinates “peak power density on the target  $q_t$  – packing factor of  $Dc$  (reciprocal of pulse ratio)”. The area  $q_t < 0.1 \text{ kW/cm}^2$  is typical for the so-called pulsing PMSdc, which includes bipolar asymmetric pulsed discharges operating in the medium-frequency band of 10–250 kHz. All discharges above the PMSdc limit are called HPPMS. In this range, the high peak power should be compensated by a lower pulse ratio. It gives the limiting power density line for the rectangular shape of the pulses shown in figure 1. The range for HiPIMS is defined by the limit  $q_t > 1.0 \text{ kW/cm}^2$ . The pulses in MPP methods tend to have a low power density



level, often in the PMSdc range, followed by a stronger pulse with an intermediate density ( $0.1 < q_t < 1.0 \text{ kW/cm}^2$ ) or even in the HiPIMS range.



**Figure 1.** Types of pulse discharges: 1 – PMSdc; 2 – MPP; 3 – HiPIMS and range: 4 – PMSdc; 5 – HPPMS [1].



**Figure 2.** The argon density  $n_{Ar}$  at magnetron sputtering depending on the power density on the target  $q$  [15].

HiPIMS systems usually operate at a voltage of 500–2000 V, current density up to 3–4 A/cm<sup>2</sup>, a peak power density of 0.5–10 kW/cm<sup>2</sup>, a pulse time of 50–100  $\mu$ s, a pulse-recurrence frequency of 50–5000 Hz, and a duty factor of 0.5–5% (or pulse ratio of 20–200). The average power remains unchanged although the peak power is 2–3 order-greater than that normally used in PMSdc. The range of parameters for HiPIMS is much wider than there are in the dc, rf and MPP systems. There is more flexibility in controlling the deposition of films due to the additional parameters such as the duration and frequency of pulses in addition.

The main motivation for using of HiPIMS is to achieve conditions that lead to high density of sputtered atoms and high ionization of the sputtered material. A partially ionized flux of sputtered material provides a reduction in the film growth rate as compared to other sputtering methods at a equal average power (table 1).

**Table 1.** Ratio of films deposition rates [16].

Target	Ti	Cr	Cu	Al	Ta	Zr	C
$v_{HPPMS}/v_{MSdc}, \%$	15–75	29	37–80	35	22–40	15	77

Physical reasons providing the advantage of high-power sputtering are as follows:

- linear increase of the sputtering coefficient with increasing ion energy;
- change of the sputtering coefficient due to the types of particles changes participating in sputtering;
- increase of film density and self-sputtering on the substrate;
- changes of the keeping conditions of charged particles near the target at current intensity;
- superposition of sputtering and evaporation of the target.

Let's take a closer look at basic physical phenomena accompanying a high-power sputtering.

1. Emission. Ion-electron emission plays a decisive role in the formation of the magnetron discharge. When the  $\gamma$  emission coefficient  $\gamma$  is approximated, the expression [17] is used for many materials at  $E_i < 600 \text{ eV}$

$$\gamma = 0.032(0.78E_{0 \rightarrow 1} - 2\phi), \quad (1)$$

where  $E_{0 \rightarrow 1}$  – the first ionization potential, eV;  $\phi$  – work function, eV.

To describe the current-voltage characteristics of the magnetron discharge and to establish its relation to the pressure of the working gas, an effective coefficient of ion-electron emission was introduced in [17]  $\gamma_{eff}$ :

$$U \sim 1/\gamma_{eff}, \quad (2)$$

which is proportional to the ionization probability  $P(p)$ :

$$\gamma_{\text{eff}} = P(p)\gamma, \quad (3)$$

the value of  $P$  is proportional to the pressure:

$$P(p) \sim p. \quad (4)$$

It follows from (2)–(4) that when the pressure increases, the voltage on the discharge must decrease. The cause-and-effect relationships reflected by expressions (2)–(4) are also valid for describing the current-voltage characteristics of the magnetrons with hot targets. In these cases it is necessary to use the results of studies where it was found that there's a heating and density decrease near the target during sputtering because of collisions between sputtered atoms and neutral particles of the working gas.

2. Rarefaction. Numerous studies have made it possible to establish that because of collisions between sputtered atoms and neutral particles of the working gas during sputtering, the heating and rarefaction arise [1]. The decrease of gas density was established as rarefaction, since a decrease in gas density is equivalent to a pressure decrease. Sometimes the term sputtering wind is used to describe this process. The wind of spraying has a direction from the target. This decrease in the density of the working gas leads to a decrease in the number of ions, which reduces the sputtering rate and, consequently, the rate of the film deposition. The data for MSdc in figure 2 show a typical example of a change in a gas density observed in front of a copper target [15]. Extrapolation of line to the high density area that is characteristic of HiPIMS shows possible very strong rarefaction which is confirmed by many authors.

3. Ionization of sputtered atoms. The electron density close to the target is of the order of  $10^{16} \text{ m}^{-3}$  in a conventional direct current magnetron. The fraction of ionized atoms in the sputtered flux has only a few percent under these conditions. High ion density without target overheating can be achieved with HPPMS or HiPIMS with a low filling coefficient (about 1 %). In this case, the peak power on the surface of the cathode can reach several kilowatts per square centimeter and the peak electron density can be two orders higher. At the same time, the share of ionized atoms in the incident sputtered flux can increase up to 100 % [1].

4. Self-sputtering. The high degree of ionization of sputtered atoms affects the film deposition process. Some of them, due to fast Bohm diffusion in a magnetic field, will fall on the substrate. The other part can return to the target area. These accelerated in the dark cathode space ions will cause the sputtering of the target, which is called self-sputtering. In this case, the target can go into a stationary mode (it is often called self-sustaining) of self-sputtering, when the inert gas can be turned off. The condition of such a state is written in the form

$$\alpha\beta S > 1, \quad (5)$$

with  $\alpha$  – the ionization probability of the sputtered atom;  $\beta$  – the probability of the ionized atom returning to the target;  $S$  – the self-sputtering coefficient. Since  $\alpha < 1$  and  $\beta < 1$  it follows from equation (5) that self-sustained self-sputtering is attainable only in the case of  $S \gg 1$ . The effect is experimentally observed for a few materials for this reason that have a high sputtering coefficient.

5. Ion sound waves. Ion sound waves can arise in the plasma at the form of longitudinal quasi-electrostatic waves associated with ion oscillations. These waves can be excited in isotropic nonequilibrium plasma, where the electron temperature is much higher than the ion temperature [18].

In the case when the electron and ion temperatures have a small difference, the phase rate of ion sound waves is close to the thermal ion rate. It leads to a strong collisionless decay due to the energy transfer to the plasma particles.

When the amplitude of the ion sound waves increases, nonlinear effects strengthen and lead to a steepening of the wave front. However, the dispersion prevents steepening and ultimately can lead to the emergence of a special class of nonlinear ion sound waves – the so-called ion-acoustic solitons, which are stable solitary disturbances of ion density propagating in space.

6. Evaporation of the target. During high-power sputtering the target surface can be heated to the temperature at which the flux of evaporated material increases up to significant value, and its density

is given by the Hertz–Knudsen equation [10]. It can lead to a significant heating of the substrate and an increase in the growth rate of the film.

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### References

- [1] Gudmundsson J T, Brenning N, Lundin D et al. 2012 *J. Vac. Sci. Technol. A*. **30** 030801
- [2] Drache S, Stranak V, Herrendorf A-P et al. 2013 *Vacuum* **90** 176–81
- [3] Zhao X, Jin J, Cheng J-C et al. 2015 *Vacuum* **118** 38
- [4] Vitelaru C, Lundin D, Brenning N et al. 2013 *Appl. Phys. Lett.* **103** 104105
- [5] Huo C, Lundin D, Raadu M A et al. 2013 *Plasma Sources Sci. Technol.* **22** 045005
- [6] Krysa J, Zlamal M, Kment S et al. 2014 *Chem. Eng. Trans.* **41** 379–84
- [7] Holtzer N, Antonin O, Minea T et al. 2014 *Surf. Coat. Technol.* 19192
- [8] Raman P, Shchelkanov I A, McLain J and Ruzic D N 2015 *J. Vac. Sci. Technol. A*. **33** 031304
- [9] Gupta R, Pandey N, Behera L et al. 2016 *AIP Conf. Proc.* **1731** 080005
- [10] Shapovalov V I, Karzin V V and Bondarenko A S 2017 *Phys. Lett. A*. **381** 472–5
- [11] Raman P, Shchelkanov I A, McLain J et al. 2015 *J. Vac. Sci. Technol. A*. **33** 031304
- [12] Niu G-J, Li X.-C, Xu Q et al. 2015 *Nucl. Instr. Meth. Phys. Res.* **349** 45–9
- [13] Cormier P A, Balhamri A, Thomann A L et al. 2014 *Sur. Coat. Technol.* **254** 291–7
- [14] Alami J, Bolz S and Sarakinos K J 2009 *Alloys and Compounds* **483** 530–4
- [15] Anders A 2011 *Sur. Coat. Technol.* **205** S1–9
- [16] Sarakinos K, Alami J and Konstantinidis S 2010 *Sur. Coat. Technol.* **204** 1661–84
- [17] Depla D, Heirwegh S, Mahieu S et al. 2007 *J. Appl. Phys.* **101** 013301