EFRE 2020

Effect of Duty Cycle and Frequency on the Ion Current Density on Substrate and Ion/Atom Ratio in Pulsed Magnetron Sputtering of Aluminum

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In this work presents the results of a study of the influence of the **pulse frequency** and **duty cycle** on the Al **deposition rate**, the **ion current density**, the **ion/atom ratio** and **the thermal flux** on a substrate during the pulsed magnetron sputtering process.

Experiments were performed over a wide range of:

- **pulse frequencies (1 ÷ 200 kHz),**
- **duty cycle (5 ÷ 50%)**
- **peak discharge power (1 ÷ 63 kW)**

at a constant average discharge power of 1 kW. Results were compared with DC mode of sputtering.

Experimental setup

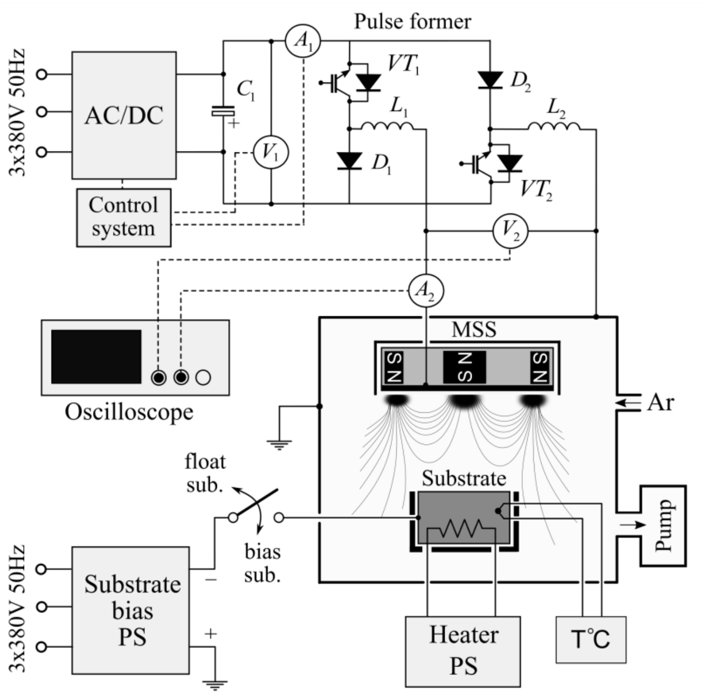

Fig. 1 - Schematic drawing of the experimental apparatus.

➢For the deposition of Al films, the APEL-MR-100 magnetron sputtering system (MSS) with a round aluminum (99.6 %) 100 mm diameter target was used. The magnetron's magnetic system was unbalanced, with a coefficient of geometrical unbalance k = 1.2. The target was sputtered at an argon pressure of 0.27 Pa. The magnetron was powered by a **pulsed-DC power supply APEL-M-10PDC-200k** produced by Applied Electronics Ltd. (Russia).

➢The substrate was either at floating potential or bias potential of -50 V. The thermal flux to a 15×50 mm^2 substrate was estimated based on the rate of change in its temperature. The temperature of the substrate with an integrated heater was controlled by a k-type thermocouple.

➢Assumed that the substrate heating during sputtering of the aluminum target was ensured by the flow of energy particles onto the unshielded substrate surface with an area of 7.5 sm2 located 10 cm from the target surface.

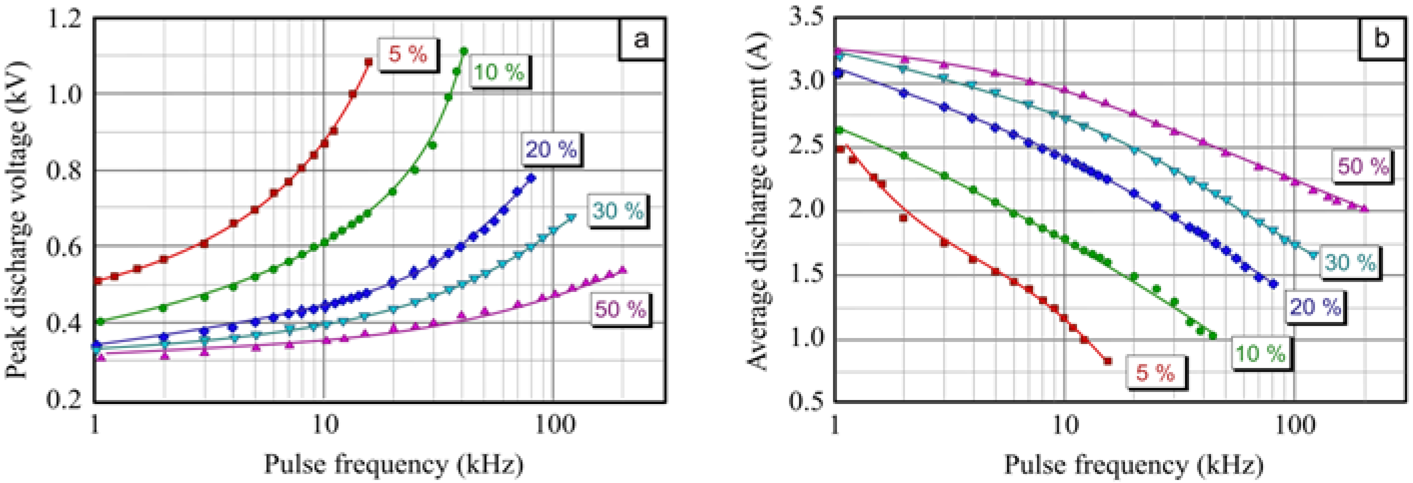

Fig. 2 - Pulse frequency dependence of the pulse discharge voltage (a), the average value of the discharge current (b).

- **The increase in the pulses frequency increases the discharge voltage.**

•A decrease of the duty cycle is also accompanied by an increase in the discharge voltage, while the dependence becomes steeper.

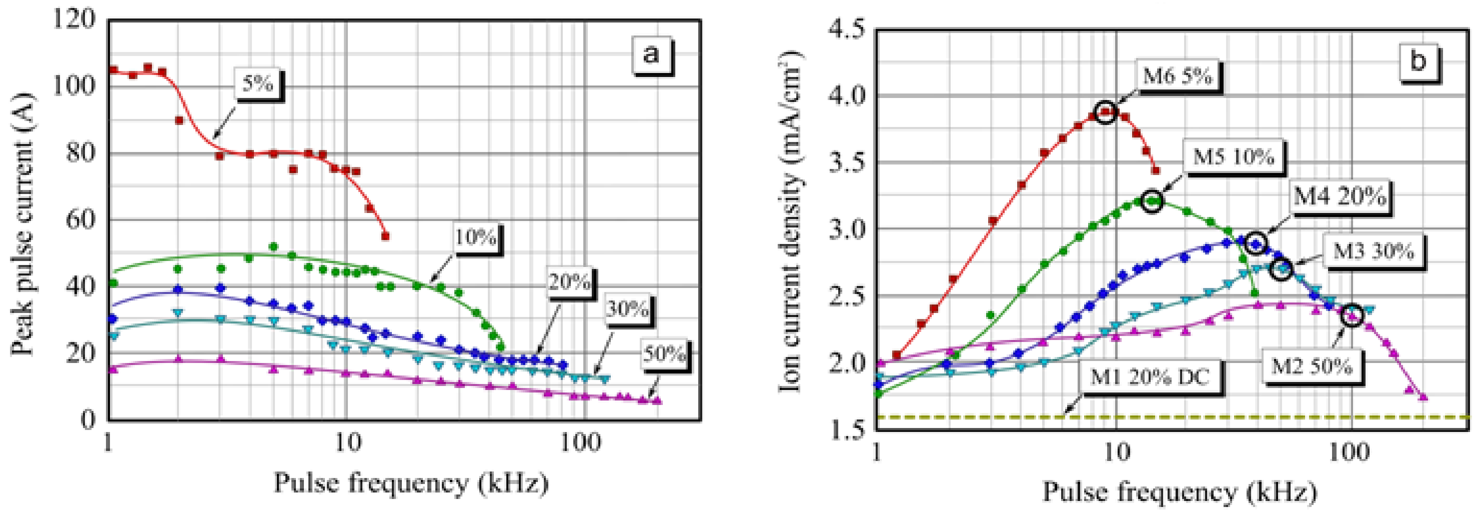

Fig. 2 - Pulse frequency dependence of the maximum value of the pulse current (a) and the ion current density on a substrate (b). Substrate bias potential -50 V.

- **For the low duty cycles, a higher ion current density is provided, however, the obtained dependences are non-monotonic**
- **For all duty cycles dependencies have a hump-like form, the hump top, where maximum ion current density is observed, with a decrease in the duty cycle becomes sharper and shifts to the lower frequencies.**
- **the duration of the discharge current pulses is in the range of 5 – 7 μs in the points where maximum ion current density is observed.**

TABLE I. ELECTRICAL PARAMETERS OF MAGNETRON SPUTTERING MODES

№	F, kHz	k, %	τ, µs	I_{ave}, A	U_p, V	Ip, A	Pp, kW
M1	DC	100	-	3.0	326	3	0.98
M2	100	50	5.0	2.2	481	7	3.34
M3	50	30	6.0	2.1	523	15	7.85
M4	40	20	5.0	1.8	603	20	12.1
M5	15	10	6.7	1.6	682	40	27.3
M6	9	5	5.0	1.3	838	75	62.9

➢**Decrease of the deposition rate while maintaining the power density transmitted to the substrate at the same level can lead to an increase in the specific energy received by the growing coating.**

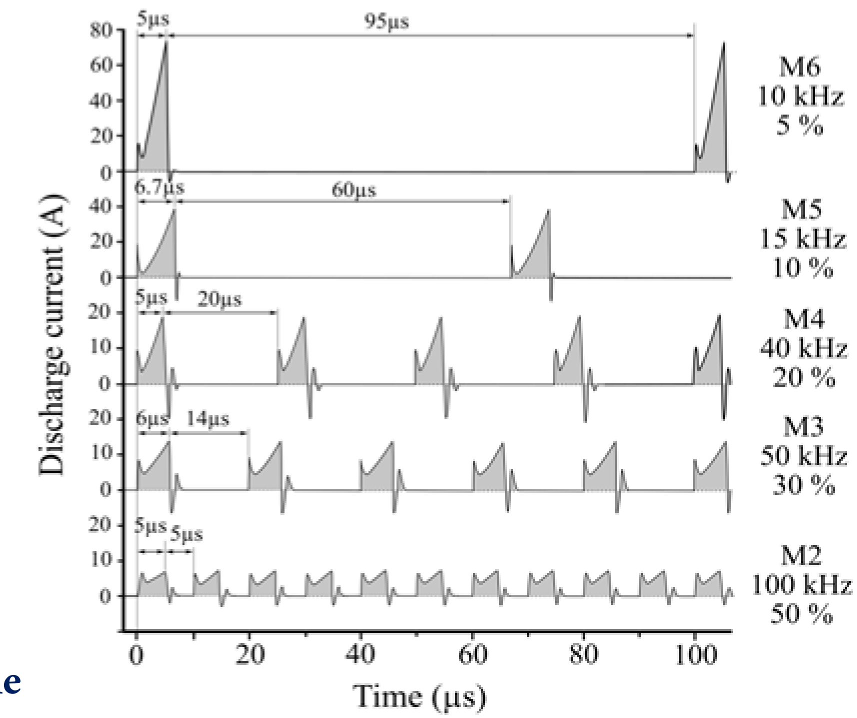

Fig. 2 - Discharge current pulses at different values of frequency and duty cycle at a fixed average discharge power of 1 kW.

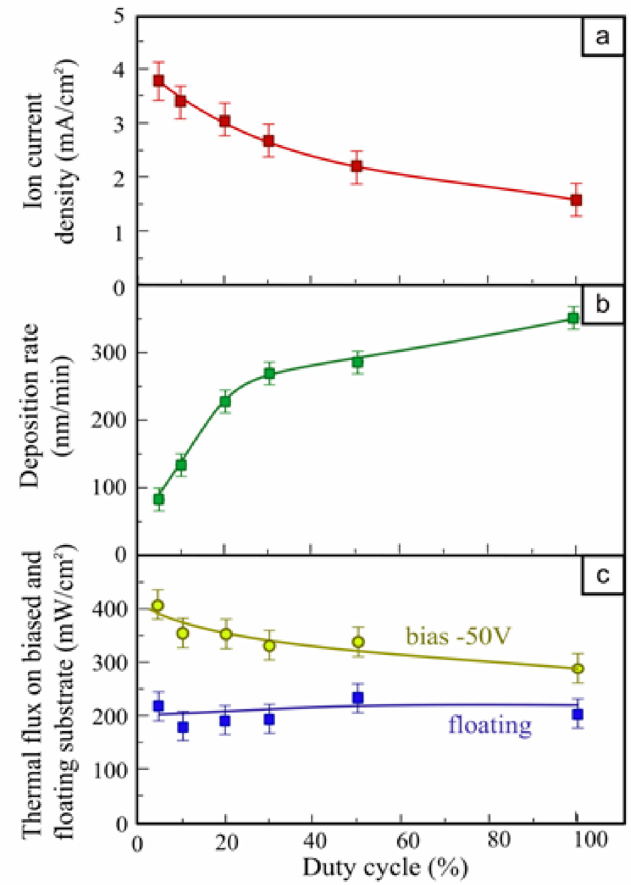

Fig. 2 - Dependences of the ion current density on the substrate (bias potential -50 V) (a), the coating deposition rate (b), the thermal flux to floating substrate, and to substrate under bias potential of -50 V (c) on the duty cycle.

TABLE II. ENERGY IMPACT PARAMETERS

Mode	Φ_i, 10^{16} $cm^{-1}s^{-1}$	Φ_n, 10^{16} $cm^{-1}s^{-1}$	Φ_i/Φ_n	E_{float}, MJ/cm^3 (eV/at)	E_{50V}, MJ/cm^3 (eV/at)
M1	1.0	3.6	0.28	0.36 (37)	0.40 (41)
M2	1.4	2.9	0.47	0.48 (49)	0.67 (69)
M3	1.7	2.7	0.62	0.44 (45)	0.75 (77)
M4	1.9	2.3	0.84	0.52 (54)	0.94 (97)
M5	2.1	1.4	1.53	0.82 (84)	1.61(166)
M6	2.4	0.8	3.15	1.77(182)	3.50(360)

Where, Φ_i – ion flux density; Φ_n – aluminum atoms flux density; Φ_i/Φ_n – ion/atom ratio; E_{float} – specific energy that the coating receives at floating substrate, E_{50V} - specific energy that the coating receives at the substrate under bias potential of -50 V.

- **There is a significant change in the specific energy transferred to the coating during its growth. At duty cycle 5 %, the specific energy transferred to the coating on a floating substrate is 1.77 MJ/cm3, which is five times higher than in DCMS mode (0.36 MJ/cm3). When bias (-50 V) is applied to the substrate, the specific energy increases to 3.5 MJ/cm3, and becomes 9 times higher than in DCMS (0.40 MJ/cm3).**

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Conclusion

- The results of the study show that the ion current density and ion/atom ratio increase with a decrease of duty cycle.
- For each duty cycle, there is an optimal pulse frequency at which the ion current on a substrate is maximum. A characteristic feature of the maximum points is the short (5–7 μs) duration of the discharge current pulses.
- Adjusting the pulses parameters allows increasing the ion current density by more than 2.5 times in comparison with the DCMS mode. Reducing duty cycle from 50 to 5% leads to a four-fold decrease in the deposition rate of Al, relative to DCMS mode.
- An increase in the ion flux density is accompanied by a decrease in the density of the film-forming particles flow to the substrate, which leads to a tenfold increase in the ion/atom ratio (from 0.28 to 3.15) in experimental conditions. The thermal flux to the floating substrate weakly depends on the frequency and duty cycle, remaining in the range of 180–220 mW/cm2.
- Thereby, it is shown that by varying the frequency and duty cycle it is possible to control the energy transmitted to the growing coating over a wide range.