UDC 533.924

DEVELOPMENT OF ARC SUPPRESSION TECHNIQUE FOR REACTIVE MAGNETRON SPUTTERING

S.V. Dudin*, V.I. Farenik, A.N.Dahov**, J. Walkowicz*****
[*]*Kharkiv National V.N. Karazin University,*
[**]*Scientific Center of Physical Technologies (Kharkiv)*
Ukraine;
[***]*Institute for Sustainable Technologies (Radom)*
Poland

Received 29.09.2005

The technique of arc suppression on the target surface of magnetron sputtering system during reactive deposition of Al_2O_3 coatings has been developed. Damping of arcs is achieved by transient polarity change of the magnetron voltage by means of a simple circuit consisting of a capacitor and an inductive coil. Practically 100% arc inhibition probability is achieved during 5 - 20 мS after its ignition. The energy input into arc before its disappearance is about 50-100 mJ. Results of experimental and theoretical investigations of the arc suppression phenomenon are presented. Process of the magnetron discharge transition to stationary state after the arc suppression has been studied too. Relaxation oscillations of current and voltage accompanying this process are described. A theoretical model of the non-stationary magnetron discharge is developed featuring its dynamic properties. Magnetron discharge dynamic impedance is found.

INTRODUCTION

It is well known that arcing is the inherent feature of the reactive magnetron sputtering of Al_2O_3 [1]. One of the main problems with aluminum sputtering in oxygen atmosphere is low minimum arc current. Stationary arc on aluminum cathode may glow at current as low as several amperes, less than regular magnetron discharge current. Therefore simple current limiting is not sufficient to prevent arcing. Using a DC current supply without arc protection will cause "long" arcs with millisecond to second duration. Such arc raises two harmful consequences: 1) metallic droplets formation reducing the quality of the growing film, 2) switching the magnetron sputtering off leading to the target poisoning and the discharge jump to poisoned mode. Common solutions of the problem are use of pulsed power supply in hundreds kilohertz frequency range, or of an active arc protection circuit switching off the DC supply not later than few microseconds after an arc detection. Both cases need extra costs, and search of a cheap alternative is actual.

A technique of passive arc protection is described here that allows using in reactive deposition any DC power supply not equipped with proper arc handling. The idea is to insert a simple resonant circuit between power supply and magnetron (see Fig. 1). In fact the circuit application does not prevent arcs, but the arcs became "short" and are damped after 5 – 10 microseconds of glowing without transition to the "long" mode. The energy deposited into arc before damping is about 50 – 100 mJ.

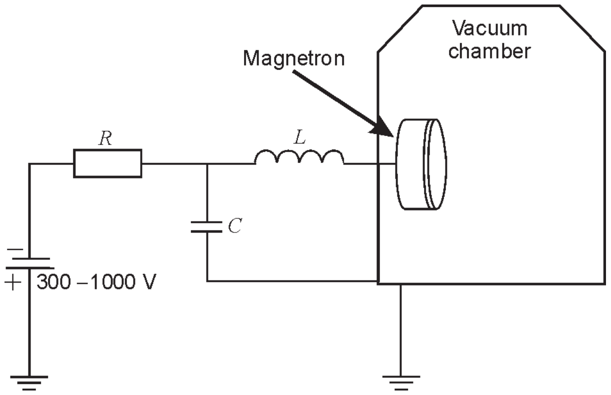


Fig.1. Schematic of the arc suppression circuit. In the experiments R = 10 Ohm, L = 19 мH, C = 1мF.

Detailed time resolved investigations of this phenomenon were performed on the experimental setup in the Kharkiv National University (Kharkiv, Ukraine) and Institute for Sustainable Technologies (Radom, Poland). The researches have proven about 100% affectivity of this technique. We observed no "long" arc during an hour despite using a simple power supply without any arc protection.

EXPERIMENTAL SETUP

In the experiments an unbalanced magnetron with aluminum target of 190 mm diameter was used. Metallic vacuum chamber was pumped-out down to residual pressure $4\cdot10^{-5}$ Torr. Measurements were carried out in atmosphere of Ar and Ar+O_2 gases. Argon pressure in all experiments was $6\cdot10^{-4}$ Torr. The magnetron anode was connected to the chamber. The schematic diagram of the arc-suppression circuit is given on fig. 1. The 10 Ohm resistor is needed to allow the capacitor voltage oscillation independently of power supply usually including high-value capacitors at output.

Time traces recording was carried out with Velleman PCS-500 double-channel digital oscilloscope. To measure high potentials a frequency compensated divider with a division ratio of 50 was used. Magnetron current was measured using 0.5 Ohm low-inductance shunt resistor.

EXPERIMENTAL RESULTS

In figure 2 typical time traces of the magnetron voltage *U* and discharge current *I* after arc ignition as well as capacitor voltage are presented.

Time evolution of the discharge can be divided into the following sections (see fig. 2):

I) arc break-down;

II) decay of magnetron plasma (“afterglow”);

III) stationary magnetron discharge recovery with the characteristic oscillations of current and voltage.

I. Arc section. Process of arc origin and development is well seen on fig. 2a and 2b. After the arc breakdown sharp magnification of discharge current occurs. The current is limited by the inductance *L*. Thus the current shape during the arc evolution has semi-cosine shape. Such pulse shape is stipulated that capacitance *C* and inductance *L* during the arc form a parallel resonant circuit. From experiment we have the oscillation half-period $T/2 = 14.6$ μS hence the resonant frequency $f = 34.2$ kHz (see fig. 2a). On the other hand the resonant frequency of the circuit $L = 19$ мH, $C = 1$ мF equals 36.5 kHz that matches well with experimental results.

In the experiment the peak value of current is 58 A. From the energy conservation $I_{peak} = 73$ A. Experimental peak value of the current is lower due to voltage drop on the discharge gap (~50 V) and *IR* drop at the shunt (~30 V).

II. Section of magnetron plasma decay. The further evolution of the discharge is well seen in fig. 2a and 2b. It may be divided into two parts:

– ***“Negative afterglow”*** (~16 μS). At the moment when $I = 0$, ignition of the discharge of reverse polarity occurs. The current is supplied with the capacitor *C* charged to reverse polarity.

– ***“Positive afterglow”*** (~20 – 30 μS). After the voltage polarity recovery the discharge current flows from the power supply through resistor R. Current polarity recovers at the same moment as the voltage.

III. Section of the stationary discharge recovery. Process of the steady conditions formation is best visible in fig. 2c. In this section capacitor *C* is charged by the power supply. The voltage rise rate ($dU/dt = 5.6$ V/μS) is determined by resistance of resistor *R*, an internal resis-

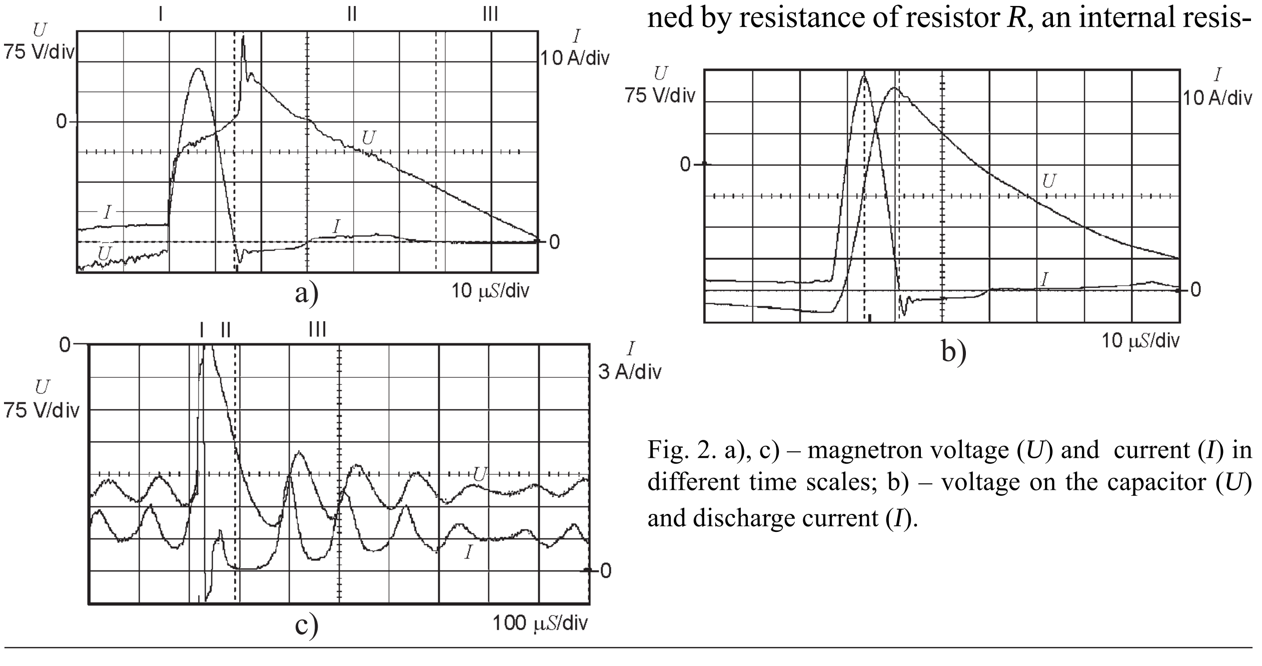


Fig. 2. a), c) – magnetron voltage (*U*) and current (*I*) in different time scales; b) – voltage on the capacitor (*U*) and discharge current (*I*).

tance of the power supply and its output voltage.

During the steady state formation ($U = 340$V, $I = 3$ A, see fig. 2c) relaxation oscillations of current and voltage are observed caused by interaction of magnetron plasma, the capacitor C and the power supply together with the resistor R.

The circumscribed behavior of magnetron plasma is observed using aluminum target both in Ar atmosphere, and in Ar + O_2 mixtures. Differences have only the quantitative character. So frequency of relaxation oscillations in Ar atmosphere is about 8 kHz, while the frequency in Ar + O_2 is more then 12 kHz. Besides the oscillations in atmosphere Ar + O_2 damp much slower.

Analysis of the experimental results shows, that relaxation oscillations in plasma can originate without the arc ignition and the subsequent pronounced section of stationary state formation, that coincides with the results of [3].

In fig. 3 the experimental current-voltage characteristic of the magnetron discharge derived from time traces of current and voltage is shown. The characteristic combines static and dynamic parts: 1 – static current-voltage diagram, relevant to the stationary magnetron discharge; 2 – dynamic current-voltage diagram, caused by availability of the relaxation oscillations in magnetron plasma.

THEORETICAL MODEL

It was mentioned above that magnetron discharge recovery after arc suppression in the present system isn't smooth and is accompanied with non-sinusoidal oscillations of magnetron current and voltage. In order to understand this phenomenon we developed a simple model describing the dynamic properties of magnetron discharge. A brief description of the model is presented below.

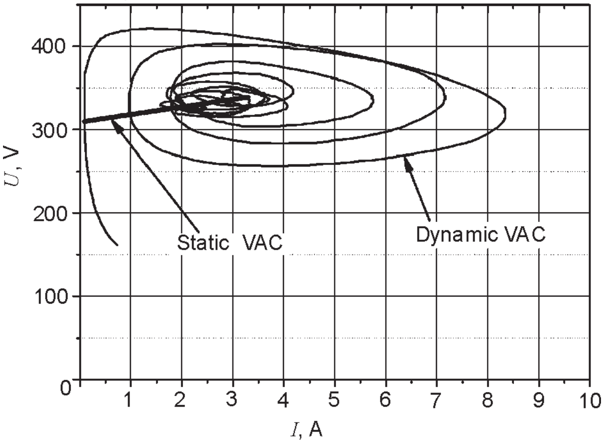


Fig. 3. The experimental current-voltage characteristic of the magnetron discharge derived from time traces of current and voltage.

Stationary state. Firstly let us define stationary state parameters of magnetron discharge following [6] and using the definitions: I – current of the magnetron discharge; U – voltage on the magnetron target versus anode; γ – ion-electron emission coefficient; $I_\gamma = \gamma I$ – current of γ-electrons; $I^i = I\dfrac{\gamma U}{\eta}$ – ionization current; з – the specific energy of ion creation taking into account electron loss [6]. In stationary state $I^i = I$, therefore $U = U_0 = \eta/\gamma$. If we state $\gamma = 0.1$, and $\eta = 50$ eV, then the steady state magnetron discharge voltage $U_0 = 500$ V.

Non-stationary model. If $U \neq U_0$, the current is not stationary, and time dependencies must be treated. Particle balance equation (plasma is considered as homogeneous medium):

$$I^i - I_i = Ve\frac{dn}{dt},$$

where I_i – ion current from the plasma, V – volume of the plasma, n – the plasma density.

If we consider for simplicity I_i is independent on U, then $I^i - I_i = \left(\dfrac{U - U_0}{U_0}\right)\cdot I$.

Ion escape we shall describe by the Bohm formula: $I_i = Sen\sqrt{\dfrac{T_e}{m_i}}$,

where S – the area of the cathode surface bombarded by ions. Now we can express plasma density through current and substitute in particle balance equation:

$$\left(\frac{U - U_0}{U_0}\right)\cdot I = \left(\frac{V}{S}\right)\frac{1}{\sqrt{T_e/m_i}}\frac{dI}{dt}.$$

Here $V/S = D$ – thickness of plasma from the cathode, $\sqrt{T_e/m_i} = v_b$ – Bohm velocity.

The factor $\left(\dfrac{V}{S}\right)\dfrac{1}{\sqrt{T_e/m_i}} = \dfrac{D}{v_b} = \tau$ has dimensionality of time and formally represents ion transition time trough plasma with Bohm velocity.

Finally we have: $I = \frac{U_0}{\Delta U} \tau \frac{dI}{dt}$.

Apparently, that the solution is the exponential curve, and time constant $\frac{U_0}{\Delta U}\tau$ is determined by two factors: τ – the property of the magnetron (it is governed by the magnetic field geometry), and ΔU – the voltage deviation from equilibrium.

The calculated time traces of the discharge current and voltage together with the current-voltage characteristics are shown in fig. 4. Qualitatively they are in good agreement to both the present experimental results and to the measurements of other authors for pulsed magnetron discharge [2, 4] and for direct-current mode with a capacitor connected to the power supply output [3]. If the parameter τ is properly chosen then quantitative agreement may be achieved.

It should be noted that the described model is rather qualitative: it is based on some approximate assumptions and describes the magnetron discharge plasma as homogeneous media with constant parameters that seems not well proven for highly inhomogeneous magnetron discharge. Nevertheless the calculated time traces are quite realistic both qualitatively and quantitatively, so the model can be used in practice.

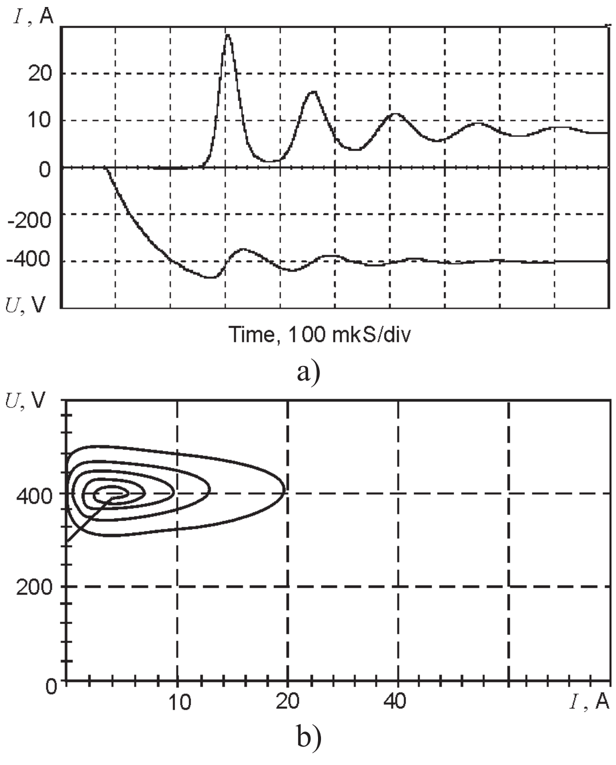


Fig.4. Calculated time traces of the discharge current and voltage (a) and current-voltage characteristics (b).

MAGNETRON DISCHARGE IMPEDANCE

Thus we have obtained the relation describing dynamic properties of magnetron discharge. It may be used to calculate the discharge impedance, that is useful for analysis of non-stationary electric circuits with magnetron load. The last expression may be rewritten in the following form: $\Delta U = L_m \frac{dI}{dt}$, where $L_m = \frac{U_0 \tau}{I}$.

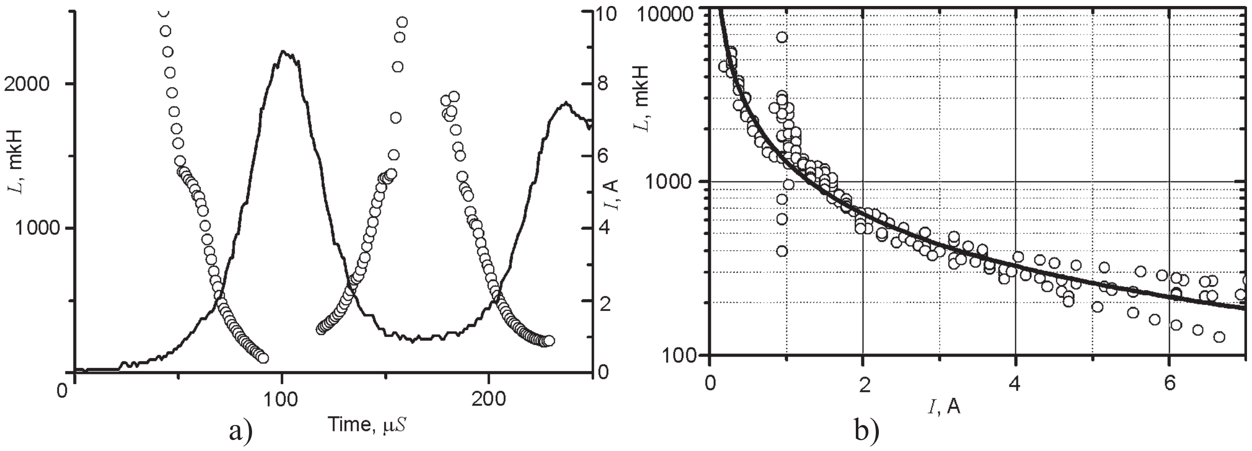
So, from the point of view of power supply the dynamic part of non-stationary magnetron discharge impedance is current dependent inductance L_m.

Let us analyze how this theoretical conclusion correlates with the experimental data. Fig. 5 shows dynamic inductivity of the magnetron discharge calculated from experimental data in the phase of the discharge recovery. One can see that the good agreement could be reached with $U_0\tau = 1300$ then $\tau = 3.8$ µS. To obtain such a value of τ in the described model we need to state $T_e = 11.5$ eV, $D = 2$ cm that looks reasonable.

CONCLUSION

We have described here the results of complex investigation of the arc suppression phenomenon that appears as a result of simple resonant circuit addition between magnetron and power supply. Basing on the research results practical constructions were applied in different magnetron installations. In all cases remarkable effect has been achieved: complete absence of “long” arcs and dramatic decrease of metallic droplets concentration in deposited films. Special efforts were directed towards the circuit optimization aiming minimization of the arc duration and energy input. The detailed research of the droplet generation and the circuit optimization issues are the subject of future publications.

It should be mentioned that such phenomenon of arc damping is possible even without the dedicated circuit applied. Output resistance and capacitance of power supply together with inductance of connecting wires may play the roles



a) b)

Fig. 5. Dynamic inductivity of the magnetron discharge calculated from experimental data in the phase of the is discharge recovery. a) – *L* and *I* change with time: dots – inductivity, line – current; b) – Dependence of inductivity on current: dots – inductivity, line – dependence *L* = 1300/*I*.

of arc-protection circuit elements. But in this case circuit operation is not controllable, and element values are unlikely optimal.

REFERENCES

1. SafiU I. Recent aspects concerning DC reactive magnetron sputtering of thin films: a review // Surface and Coatings Technology. 2000. – Vol. 127. – P. 203-219.
2. Musil J., Lestina J., Vicek J., and Tцlg T. Pulsed dc magnetron discharge for high-rate sputtering of thin films // J. Vac. Sci. Technol. A. – 2001. – Vol. 19, No 2. – P. 420-424.
3. Абдуев А.Х., Магомедов А.М. Устойчивые тоновые осцилляции при магнетронном распылении оксидных мишеней// ЖТФ. – 1998. – Т. 28, № 5. – С. 58-62.
4. Денбновецкий С.В., Хипплер Р., Кузьмичев А.И., Кулиновский В.Ю. и др. Запаздывание возникновения разряда в импульсных магнетронных распылительных устройствах// Электроника и связь. – 2000. – Т. 2, № 8. – С.195-198.
5. Kuzmichev F.I., Bevza O.N., Sidorenko S.B. The magnetron sputtering system with pulse-modulated power supply// In Proc. Int. Conf. “Plasma Physics and Plasma Technology “. – Minsk. – 1997. – Vol. 4. – P. 718-720.
6. Lieberman M. A. and Lichtenberg A. J. Principles of Plasma Discharges and Materials Processing // Wiley. – New York. – 1994.

РОЗРОБКА МЕТОДИКИ ПОДАВЛЕННЯ ДУГ ПРИ РЕАКТИВНОМУ МАГНЕТРОННОМУ РОЗПИЛЕННІ

С.В. Дудін, В.І. Фаренік,
О.М. Дахов, Я. Валькович

Розроблено методику гасіння дуг на поверхні мішені магнетронної розпилювальної системи в процесі реактивного нанесення покриттів Al_2O_3. Подавлення дуг відбувається шляхом тимчасової зміни полярності напруги на магнетроні, що досягається за допомогою простого електричного ланцюга з конденсатора та катушки індуктивності. Досягається практично 100% імовірність подавлення дуг протягом 5 – 20 мкс після їх виникнення. Енергія, що вкладається в дугу до згасання, складає 50 – 100 мДж. Надані результати експериментальних та теоретичних досліджень процесу дугогасіння. Досліджений також процес переходу магнетронного розряду до стаціонарного стану після зникнення дуги. Виявлено згасаючі коливання напруги та струму, що супроводжують цей процес. Побудовано теоретичну модель нестаціонарного магнетронного розряду, яка описує його динамічні властивості. Знайдено динамічний імпеданс магнетронного розряду.

РАЗРАБОТКА МЕТОДИКИ ПОДАВЛЕНИЯ ДУГ ПРИ РЕАКТИВНОМ МАГНЕТРОННОМ РАСПЫЛЕНИИ

С.В. Дудин, В.И. Фареник,
А.Н. Дахов, Я. Валькович

Разработана методика гашения дуг на поверхности мишени магнетронной распылительной системы в процессе реактивного нанесения покрытий Al_2O_3. Подавление дуг производится путем кратковременной смены полярности приложенного к магнетрону напряжения при помощи простой электрической цепи, состоящей из конденсатора и катушки индуктивности. Достигается практически 100% вероятность подавления дуг в течение 5 – 20 мкс после их возникновения. Энергия, вкладываемая в дугу до ее исчезновения составляет 50 – 100 мДж. Представлены результаты экспериментальных и теоретических исследований процесса дугогашения. Исследован также процесс перехода магнетронного разряда к стационарному состоянию после подавления дуги. Обнаружены затухающие колебания тока и напряжения, сопровождающие этот процесс. Построена теоретическая модель нестационарного магнетронного разряда, описывающая его динамические свойства. Найден динамический импеданс магнетронного разряда.