THE ENERGY BALANCE OF THE ASYMMETRIC COMBINED INDUCTIVE-CAPACITIVE RF DISCHARGE AT LOW PRESSURE

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The combined inductive-capacitive RF discharge at low gas pressure is considered for a case of collisionless ion motion. The power distribution model in the combined RF discharge in case of two asymmetric RF electrodes is developed in term of a ratio of the electrode areas and in term of a magnitude of applied RF voltage. We believe that power distributes on three parts: ionization and acceleration of ions in two electrode-sheath transitions. Two types of design is considered: with one and two RF generators. The dependencies of the dissipated RF power parts are obtained in terms of external discharge parameters. It is revealed an existence of a power maximum on acceleration of ions at electrode, which has a lower area. Been accorded expression for dependence of optimum discharge parameters. At using the power distribution model results the system parameter correlation's have been obtained for a maximum process effectiveness of physical sputtering for systems on the basis of combined inductive-capacitive discharge.

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INTRODUCTION

At present inductively coupled discharges are widely used as plasma sources in various technologies for plasma processing. A high plasma density ($10^9 \div 10^{12}$ cm^{-3}), low ion energy losses per ion creation [1] and the feasibility of stable operation at low pressures without any heated elements or magnetic fields are just some of the advantages of inductively coupled RF discharge as the plasma forming stage in ion-plasma processing systems [2,3]. Since inductively coupled RF discharges have not displacement current in comparison with capacitive RF discharge, they are so called "electrodeless" discharges. Due to this feature in inductively coupled plasmas ion energies are relatively low and it results in a decrease in ion-wall interaction. At using an additional DC or RF biasing this makes processes of ion production and ion acceleration to be independent. In many applications the ions formed in the inductive discharge volume are normally additionally accelerated by a self-bias voltage formed between two powered electrodes of different areas to which an RF voltage has been applied [4]. For example, a single-grid RF ion source for etching the surface of solids [5] (see Fig.1), or systems for deposition of thin films by multiple sputtering of a solid target [6]. In industrial sputtering systems it is convenient to use a common RF generator and matching system to supply power to the inductor and to the electrodes. Such design allows eliminate the mutual influence of the two generators. In such systems the power is automatically redistributed between the inductive coil and powered electrodes. When designing these sputtering systems, the parameters must be specifically selected to maximize the energy input to the sputtered target electrode or to the ion source beam.

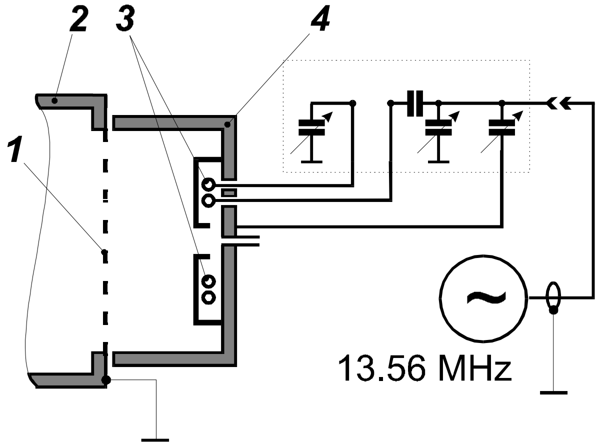


Fig.1 One-grid ion sources based on a combined inductive-capacitive RF discharge, (1) – grounded grid-electrode of accelerating system; (2) – grounded vacuum chamber; (3) – two turn screened inductive coil;
(4) – powered electrode

The system described with a common RF generator is essentially a single, combined, inductive-capacitive RF discharge. Although numerous studies dealing with the physics of inductively coupled discharges [7,8] and electrode layers [9,10], and also patents [11,12] have been published recently, the combined inductive-capacitive discharge has been virtually ignored and the available data are insufficient to optimize the design of sputtering systems in term of energy.

The aim of the present study is to make a theoretical analysis of the power distribution in a sputtering system based on a combined inductive-capacitive RF discharge and to optimize the ratio of the system parameters in terms of energy input to the target or ion beam.

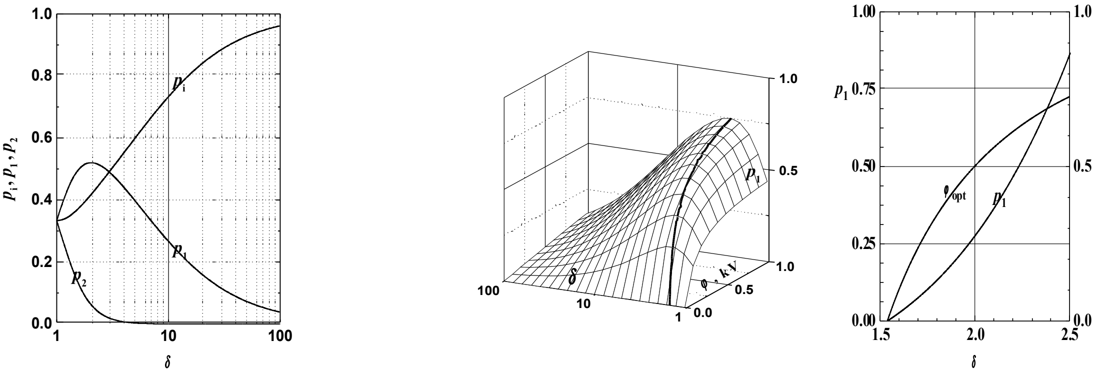
DISCHARGE MODEL

As a result of the analysis we develop a phenomenological model of the energy balance in the inductive-capacitive RF discharge. The limits of validity of the model are governed by the following conditions:

(1) The analysis is made for low-pressure range ($p < 10^{-2}$ Torr) of working gas, which is preferred to the sputtering systems. In this range it can approximately be assumed that (i) the motion of the ions and sputtered particles is collisionless and (ii) the ionization is constant over the volume, which gives uniform ion current density j on the surface of the gas-discharge chamber.

(2) The inner surface of the gas-discharge chamber is formed only by the surface of the two electrodes with areas A_1 and A_2 ($A_1 < A_2$ and $A_1 + A_2 = A_0$). The areas of the other surface bounding the plasma are negligible.

(3) We assume that the plasma is enough dense and the



a **b** **c**

Fig. 2 Dimensionless powers p_1, p_2 *and* p_i *versus ratio of electrode areas* $\delta = A_2/A_1$ *for* $\varphi = 300$ *V (a) and versus* δ *and* φ *(b). The bold line on the surface* $p_1(\varphi,\delta)$ *shows the maximal magnitude of* p_1 *at the fixed* φ_{opt}*. The maximal magnitude* p_{1max} *and value of* φ_{opt} *versus the electrode areas ratio* δ *is shown at Fig.2(c). The results present the case of low pressure when* $\alpha = 4$ *and* $\eta \approx 80$ *V/ion (for working gas – Argon)*

thickness d of electrode layers is small, so that $d \ll L$, where L is the characteristic size of the gas-discharge chamber (for example, for $L = 10$ cm and $U = 1000$ V we impose the limitation $j > 0.2$ mA/cm^2).

(4) The ions are accelerated by a quasi-steady state, time averaged potential drops U_1 and U_2 in the sheathes near the electrodes with areas A_1 and A_2 respectively, i. e. the ion transit time in the electrode sheathes is much greater then the period of the RF field. This imposes a constraint on the operating frequency f (for $d = 1$ cm and $U = 1000$ V we require that $f > 3$ MHz).

The distributions of the supplied power P_0 may be represented as $P_0 = P_1 + P_2 + P_i$, where $P_1 = jA_1U_1$ and $P_2 = jA_2U_2$ are the power dissipated in accelerating the ion fluxes to the electrodes and $P_i = jA_0\eta$ is the power dissipated in the formation of ions. The parameter η is the energy losses per ion creation, which consists of electron energy losses in inelastic processes and kinetic losses due to thermal motion of ions and electrons. We express the biases U_1 and U_2 in terms of the amplitudes φ_1 and φ_2 of the RF voltage applied to the layers: $U_1 = \varphi_1$ and $U_2 = \varphi_2$. According to Refs. [9,10] φ_1 and φ_2 are related as $\varphi = \varphi_1 + \varphi_2$ and $\varphi_1/\varphi_2 = (A_2/A_1)^\alpha$, where φ is the amplitude of the RF voltage applied between the electrodes. For collisionless ion motion, when Child-Langmuir law is valid, $\alpha = 4$ [9].

$$p_i = \left[1 + \beta(\delta)\cdot\left(1 + \delta^{\alpha-1}\right)\cdot\frac{\varphi}{\eta}\right]^{-1},$$

$$p_1 = p_i\cdot\beta(\delta)\cdot\delta^{\alpha-1}\cdot\frac{\varphi}{\eta},$$

$$p_2 = p_i\cdot\beta(\delta)\cdot\frac{\varphi}{\eta},$$

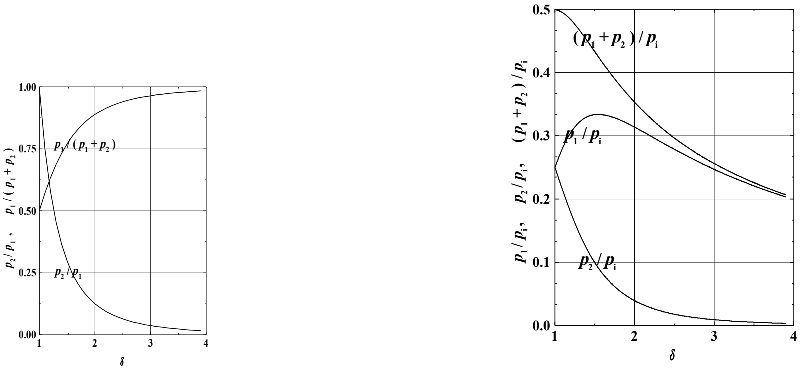
where

$$\beta(\delta) = \frac{\delta}{(1+\delta^\alpha)(1+\delta)}.$$

Note that p_1 may be considered as the useful part of the supplied power or, in dimensionless form, as the system energy efficiency.

DISCUSSION

For the case of collisionless ion movement, when $\alpha = 4$ [9], the power distributions are plotted in term of the parameter δ in Fig. 2a. Attention is drawn to the maximum of p_1, which position depends on φ, i.e., for every value of φ there is the optimum of δ for the maximum efficiency. The bold line on the dependence of p_1 versus φ and δ in Fig. 2b shows a location of the maximum of p_1. Fig. 2c gives the optimum of δ and the maximum efficiency as function of φ. This curve can be used directly to design the sputtering systems. Having



a **b**

Fig. 3 Correlation's between the applied power components p_2/p_1, $p_1/(p_1+p_2)$ *(a) and* p_1/p_i, p_2/p_i *(b) versus* δ *(*$\varphi/\eta = 1$*)*

defined the required value of φ (for $\varphi > 100$ V and $\delta > 1.5$, φ is almost the same as the accelerating voltage U_1), we can use these curves to find the optimum ratio of electrode areas.

The expressions - are convenient for power balance computation in combined inductive-capacitive RF discharge with common RF generator for ionization and acceleration of charged particles (see Fig. 1).

In the case of independent RF power supplies for creation and acceleration of ions it is more convenient following expressions:

$$\frac{p_2}{p_1} = \frac{1}{\delta^3}$$

$$\frac{p_1}{p_1 + p_2} = \frac{\delta^3}{1 + \delta^3}$$

$$\frac{p_1 + p_2}{p_i} = \frac{\varphi}{\eta} \cdot \frac{\delta(\delta^2 - \delta + 1)}{(\delta^4 + 1)}$$

$$\frac{p_1}{p_i} = \frac{\varphi}{\eta} \cdot \frac{\delta^4}{(1+\delta)(1+\delta^4)}$$

$$\frac{p_2}{p_i} = \frac{\varphi}{\eta} \cdot \frac{\delta}{(1+\delta)(1+\delta^4)}$$

The dependencies - are given in Fig. 3. As it follows from this figure the most of RF power for ion acceleration is dissipated on smallest electrode at ratio of electrodes areas $\delta > 1.55$.

CONCLUSION

We have therefore made a theoretical analysis of the power distribution in sputtering system based on an inductive-capacitive discharge. We have established that there is an optimum ratio of electrode areas ensuring maximum energy input to the target, and we have calculated this ratio as a function of the external parameters. The theoretical conclusions are universal and can be applied regardless of the absolute values of the input power and target size. The results may be used directly to design sputtering systems based on inductive-capacitive discharges and may also be useful for further development of physical models of gas-discharge systems.

In conclusion we note that the approximation of constant ion energy value (η = const) has been used in this study. In general however η is function of pressure, the potential φ and other factors [1]. The authors intend to carry out further investigations to verify experimentally the influence of these factors on the energy balance and to refine the theoretical model.

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ЕНЕРГЕТИЧНИЙ БАЛАНС В АСИМЕТРИЧНОМУ КОМБІНОВАНОМУ ІНДУКЦІЙНО-ЄМНІСНОМУ ВЧ РОЗРЯДІ НИЗЬКОГО ТИСКУ

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У роботі розглядається комбінований індукційно-ємнісної ВЧ розряд в області низького тиску робочого газу, коли іони досягають стінок розрядної камери без зіткнень. Для випадку асиметричних ВЧ електродів побудована феноменологична модель балансу потужності, що підводиться до ВЧ розряду в залежності від відношення площ ВЧ електродів і амплітуди прикладеного ВЧ потенціалу. Розглянуті два типи систем: з одним і двома ВЧ генераторами. Отримана залежність складових потужності, що поглинається в розряді в залежності від зовнішніх параметрів розряду. Виявлено існування максимума потужності на прискорення іонів на електрод меншої площі. Знайдена залежність положення даного максимума від параметрів системи. Результати можуть бути використані як при конструюванні й оптимізації розпилювальних систем на базі комбінованого розряду, так і для подальшого розвитку модельних уявлень про фізику ВЧ розрядів.

ЭНЕРГЕТИЧЕСКИЙ БАЛАНС В АСИММЕТРИЧНОМ КОМБИНИРОВАННОМ ИНДУКЦИОННО-ЕМКОСТНОМ ВЧ РАЗРЯДЕ НИЗКОГО ДАВЛЕНИЯ

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В работе рассматривается комбинированный индукционно-емкостной ВЧ разряд в области низкого давления рабочего газа, когда уход ионов из плазмы на стенки разрядной камеры происходит без столкновений. Для случая асимметричных ВЧ электродов построена феноменологическая модель баланса подводимой к разряду ВЧ мощности в зависимости от отношения площадей ВЧ электродов и амплитуды приложенного ВЧ потенциала. Рассмотрены два типа систем: с одним и двумя ВЧ генераторами. Получены зависимости составляющих поглощаемой в разряде мощности в зависимости от внешних параметров разряда. Обнаружено существование максимума мощности на ускорение ионов на электрод меньшей площади. Найдена зависимость положения данного максимума от параметров системы. Результаты могут быть использованы как при конструировании и оптимизации распылительных систем на

базе комбинированного разряда, так и для дальнейшего развития модельных представлений о физике ВЧ разрядов.