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Ion sputtering of cathode surface in a hollow cathode discharge

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Abstract

In this paper, ion sputtering of cathode material in a specific type of glow discharge—hollow cathode discharge (HCD)—is analyzed. To estimate both real sputtering yield and screening effect of the buffer gas, two different methods—combination of experimental and analytical approach (applicable for Ar buffer gas only) and use of Monte Carlo simulations—are used. The latter, which is introduced for the first time here, can be used for any buffer gas. Real sputtering yield S_k is estimated by Monte Carlo simulations for several commercial HCD lamps with Ne buffer gas: Ne–Li (0.046), Ne–As (0.862), Ne–Ca (0.337) and Ne–Cd (1.069).

Keywords: Hollow cathode discharge; Cathode surface sputtering; Screening effect

1. Introduction

Ion sputtering of the cathode surface is a characteristic process of some types of gas discharge plasma. Apart from the technological aspects (thin film deposition, ion etching, etc.) [1], this process adds atomic species of cathode material to buffer contributing to enrichment of the plasma spectrum [2–5]. Hollow cathode discharge (HCD) is a glow discharge modification characterized by intensive cathode sputtering, which makes it a reservoir of sputtered atoms in ground state. This discharge is widely used as a light source in atomic spectroscopy since, among other useful properties, it allows avoiding more complicated atomization methods [6,7]. Hence, HCD is also known as a discharge with enhanced Penning ionization (metallic atoms have low ionization potential), which is a process of particular scientific interest [7]. Consequently, estimation of the sputtering yield in HCD is a task of present interest from both technological and fundamental point of view.

Data on sputtering yield in vacuum using monoenergetic ion beams with different incident angles (cf. Ref. [8] for instance) cannot be used in the case of real plasma since the ambient gas reduces the sputtering yield by screening effect [9]. In addition, usually, the data refer to the bombarding ion of relatively high energy (above 1 keV), which exceeds considerably that in the gas discharge plasma.

Two options for estimating the sputtering yield in HCD are presented in this work. The estimation is divided into three steps: (1) calculation of the mean kinetic energy of bombarding ions; (2) determination of the sputtering yield in the case of ion bombardment of the cathode surface in vacuum; and (3) considering the screening effect of buffer atoms. Although every step is far from trivial, we find the third one particularly complicated. Here, we present two alternative methods for step 3, the first one being already present in the literature [10], while the other one, based on the Monte Carlo simulation, is introduced here for the first time. While the former has been developed for the Ar buffer gas only, the latter has general advantage that it can be used for any buffer gas. Hence, one of the tasks of this paper is to compare the two mentioned methods by calculating sputtering yield of the Ca and Cd electrodes in Ar HCD. The second method (Monte Carlo simulations) is then employed for estimating the sputtering yield of four different electrodes (As, Li, Cd and Ca) in Ne HCD.

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2. Sputtering yield calculation in HCD

2.1. Basic remarks

The commensurability of the large contact surfaces—Negative Glow (NG)–Cathode Dark Space (CDS)–Cathode—predetermines decisive role of the γ and sputtering processes at the HCD cathode. Near the CDS, the ion may be extracted from the NG and accelerated across the cathode fall potential U_c in the CDS. An energetic ion impinging the cathode surface is either backscattered from a surface atom or penetrates the solid and transfers all of its energy to the surface atoms [7]. The latter may cause sputtering if the ion energy W_s is high enough. After the ion energy is determined from the discharge parameters, sputtering yield of the cathode surface can be determined assuming normal incidence and that the target is in vacuum. Sputtering yield in vacuum conditions can be calculated by theoretical models, obtained using different simulations, or determined experimentally. Finally, the screening is calculated from the pressure and the cross-section for the elastic collisions between the cathode atoms and the buffer gas, which mainly contribute to the thermalization of the sputtered particles.

2.2. Calculation of the sputtering yield

The value of W_s depends on the electric field E_s in the CDS, the ion-free path λ_i and the CDS length l. At the cathode surface $E_s = E_{max}$ and $W_s = eE_{max}\lambda_i$. If we approximate the electric field distribution as $E(x) = E_{max}(1-x/l)$, where $x = 0$ is the coordinate at the cathode surface, E_{max} can be calculated [11]:

$$U_c = \int_0^l E(x)\mathrm{d}x = \int_0^l E_{max}\left(1 - \frac{x}{l}\right)\mathrm{d}x$$
$$= \int_0^l E_{max}\mathrm{d}x - \int_0^l E_{max}\frac{x}{l}\mathrm{d}x = E_{max}l - E_{max}\frac{l}{2} = \frac{1}{2}E_{max}l.$$

Consequently, $E_{max} = 2U_c/l$. As $W_s = mV^2/2 = eE_{max}\lambda_i = 2eU_c\lambda_i/l$ and $\lambda_i = [n\sigma(V)]^{-1}$, where n is the density of buffer atoms and V and m are the bombarding ion velocity and mass, respectively; $\sigma(V)$ is cross-section of the resonant charge exchange for buffer gas. The last relation can be rewritten as

$$\frac{eU_c}{l} = \frac{mp}{4kT}V^2\sigma(V), \qquad (1)$$

where the relation for ideal gases $p = nkT$ (k is Boltzmann constant and T is the gas temperature during the pressure measurement) is used.

From this equation, if $\sigma(V)$ is known, the mean kinetic energy of bombarding ions can be directly calculated (Fig. 1).

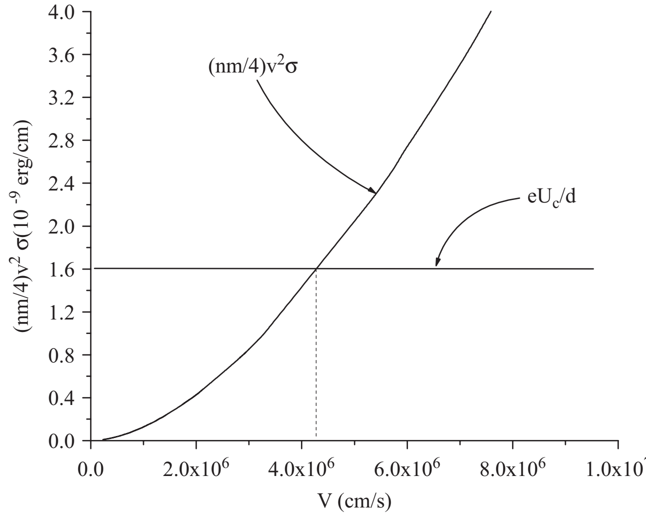

Fig. 1. Graphical calculation of Eq. (1) for Ne bombarding ions.

Both experimental determination and calculation of the sputtering yield in the low energy region (below 1 keV) are complicated tasks. Discrepancy between existing experimental results sometimes exceeds 50% [12]. Moreover, data are not available for many targets and then the sputtering yield can be obtained by extrapolation of the experimental data. Alternatively, different theoretical models can be used (such as widely accepted Sigmund model [13]), but they are not reliable in this energy region. A better option is to use Monte Carlo or Molecular Dynamics simulations to determine the sputtering yield although significant discrepancy from the experimental results can be expected [14].

According to the method given in Ref. [9], the screening effect of buffer atoms is determined as the relation between the real sputtering yield S_k and that obtained in vacuum S: $(S-S_k)/S = \varphi(p\cdot h)$, where h is a distance along which the thermalization of just sputtered atoms occurs due to elastic collisions with atoms of the buffer gas and p is the pressure. It is assumed that only atoms originating from the cathode which are transmitted through the gas target are those that are going to be sputtered. The others, which are stopped in the gas target, will return to the surface due to the back diffusion. The distance h depends on the initial energy of sputtered atoms, their mean-free path through the buffer gas, the cross-section for the elastic collision with gas atoms and the mean energy transferred in these collisions. The calculations of the distance h in typical HCD conditions show that the thermalization occurs in the CDS [2,9]. The function $\varphi(p\cdot h)$ is tabulated for argon buffer gas in Ref. [9]. An alternative for calculating the screening effect would be to use Monte Carlo method to simulate the transport of sputtered particles through the buffer gas. In that case, according to the model given in Ref. [9], S_k/S equals the number of sputtered atoms that are transmitted through the buffer gas with thickness h and pressure p divided by the number of the atoms that would be sputtered in vacuum conditions. Obviously, the latter method can be applied for any buffer gas.