

# Ion Source and Vacuum Chamber, Influence of Various Effects on Ion Beam Parameters

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Since 1970s the ion source became a valuable tool in the thin film technology. At first there were utilized the so-called gridded ion sources that usually could provide broad ion beams of various gases (noble and reactive) with comparatively high ion beam energies from about 100 eV and up to about 1000-1500 eV. However, in the gridded ion sources, due to a space charge limit, it is hard to obtain high ion beam currents at low energies. Since late 1980es with introduction of Hall-current ion sources also called as closed drift of magnetic and anode layer [17], end-Hall [13], it became possible to have ion beam currents of several Amperes (up to 5-7 A at present time) at low energies of about 70-125 eV. Such high ion beam currents found broad application in varieties of thin film and optical deposition tasks. Low ion beam energies is happened to be especially valuable for the techniques that allow obtaining very high quality thin films with an ion beam assisted deposition (IBAD), a biased target deposition (BTD), a magnetron ion assisted deposition (MIAD), and even for sputtering-etching. In most cases, it is necessary that ion beam energy will be below the sputtering energy threshold, and deposited thin films will be just packed, impact in necessary way and not sputtered.

In order to utilize the planned broad ion beam current and energy, it is necessary to provide the conditions for an ion beam that are applied to a target, or a substrate. It is necessary to have an ion beam without influence of various factors that can significantly change an applied ion beam, or these factors must be minimized. These factors include:

1. Influence of unaccounted increase of additional mass flow into ion source discharge channel caused by insufficient pumping or too small dimensions of vacuum chamber, or too big ion source for a vacuum chamber; insufficient pumping also develops dangerous oscillations and instabilities [we already discussed this problem in *VT&C*, 1];
2. Charge exchange effects that are important at high test facility background pressure;
3. Presence of double ionized particles and theirs impact on ion beam energy;
4. Impact of a vacuum chamber pumping rate on maintaining normal range of operation parameters;

5. Dielectric depositions on anode during operation with reactive gases;
6. Returned sputtered particles into an ion source with development of dielectric films on discharge channel surface, substantially influencing ion source operation;
7. Influence of ion source heating on its operation;
8. Negative ions and theirs role in ion beam process.

All these factors need to be analyzed; ion source dimensions with necessary operational parameters should be selected for any particular task.

There will be discussed a series of physical effects that can influence the ion sources performance and on the thin film process. There will be estimated these effects and conditions they can be ignored or how to reduce their influence.

It is well-known fact that ion sources is a spin-off from development of electric propulsion devices, or thrusters that utilized in space for movement of satellites and other spacecrafts.

The ion source/thruster (IST) in a vacuum chamber is quite different physical object in comparison with thruster in space. In space, behind a thruster's exit there is, in general, a beam of fast ions and neutralizing its volumetric electric charge a cloud of electrons coming from a cathode-neutralizer (though the satellite's parts and solar panels can participate in returning some particles back into a thruster). In a vacuum chamber, there are some different components participating in an ion beam process. First of all, there are specific "boundary conditions": vacuum chamber's walls, cryopanel, or the holes from vacuum pumps. Together with plasma a neutral gas (for example Ar, or other reactive gases, mainly O<sub>2</sub>) is a part of gas system, a secondary plasma (Ar<sup>+</sup> + e), a flow of sputtered particles (T<sup>+</sup>, T, T<sup>0</sup>) from a target (or targets), admixture of gases (pump's oil, air from outside, or water vapors absorbed after chamber's opening, and others). An electric field is also quite complex in comparison with the space conditions. All this system that is far from equilibrium can be called "vacuum chamber dynamic system" (VCDS) [2]. This system requires the kinetic description.

The Knudsen's parameters are playing a fundamental role in the analysis of processes

in VCDS:

$$(Kn^{\alpha\beta})_N = \lambda_{\alpha\beta}^N / L. \quad (1)$$

Here  $\lambda_{\alpha\beta}^N$  is a mean free path of particles of  $\alpha$ -kind in the particles of  $\beta$ -kind with respect to  $N^{\text{th}}$  process (elastic collisions, charge-exchange, ionization, and others),  $L$  is the characteristic space scale of the system (for example, a vacuum chamber's diameter).

There is opinion that the thin film depositions, or other fine ion beam interactions with surfaces of different materials are "pure" at low pressure, or the larger a  $Kn$  number for elastic collisions of fast ions Ar<sup>+</sup> with a residual gas. However, it is necessary to have in mind that there is a very intensive sputtering of different targets by an ion beam, because, for example, at ion energy of about 300 eV every ion knocks out approximately 1 particle from a target. Thus, at  $(Kn)_{el} \geq 1$  in vacuum chamber there are two sources of particles: an ion source and target (or targets). The particles coming from a vacuum chamber into an ion source's channel can "poison" an ion source's working surfaces.

This phenomenon is well known to those who operate ion sources in vacuum chambers with walls covered by easy sputtered material (like stainless steel, or Aluminum foil that after the first 2-3 hours of operation before it becomes oxidized, especially if the working gas is Oxygen; with Argon as working gas Aluminum foil becomes oxidized after several vacuum chamber opening and becomes less sputtered), or, when an ion source is directed to a reflecting surface (target, or an opposite to an ion source's wall).

From the above said follows, that ideally it's good to have targets that do not sputter and do not return particles back to ion source's discharge channel. **The best targets can be the gas targets**, but for this, it is necessary to comply the condition  $(Kn)_{el} = \lambda/L \ll 1$ . Here,  $L$  is a vacuum chamber's length. At the same time, pressure at ion source's exit must be sufficiently small that there will be no influence on an ion source's operation. In order to perform these two contradictory conditions it is necessary to provide a detailed analysis of the processes taking place in vacuum chamber.

Appearance of sufficiently fast particles (not necessarily from an ion source) into vacuum chamber walls covered by loose layers of particles came from a sputtered tar-

get (that happens with many vacuum chambers operated with ion sources) plays a big role in a formation of plasma composition in a vacuum chamber. Such layers are easy sputtered and come into VCDS.

Finally, the properties of the ion source working surfaces (anode, reflector, discharge channel, hot filament), a vacuum pump oil and covers of the vacuum chamber walls influence on every specific vacuum conditions in a vacuum chamber.

Appearance of the vacuum chamber's particles into an ion source discharge channel leads into a series of consequences, such as:

Neutral atoms that appeared in a discharge channel are ionized by drifting electrons. In a result, a discharge current increases at least by the value:

$$\delta I_d = eN_{in}, \quad (2)$$

where  $N_{in}$  is a number of particles coming into a discharge channel per time unit and ionized there.

Additional number of neutral atoms in a discharge channel with further ionization of these atoms can lead to the increase and decrease of an ion beam current depending on operation conditions. Also, these particles can restructure E-field in a discharge channel, usually with negative consequences.

Electrical conductivity plays a fundamental role in electron transfer across magnetic field. Sputtering of discharge channel parts by dielectric or conductive materials substantially changes regular configuration of E-field. A disruption of regular electrical conductivity by dielectric or conductive materials leads to a discharge restructuring. Oscillation level sharply increases. In a result, ionization becomes not sufficiently efficient, particles ion energy spread increases, an electron temperature also increases, an ion beam changes its form. However, in some other cases, appearance in a discharge channel of particles leading to a decrease of ionization ability will help to reduce an electron temperature and, as a result, leads to a decrease of ionization degree. And, this also reduces an ion beam current.

These phenomena were experimentally supported [2] and they confirm that, in general, discharge in an ion source can be called as a "surface-dominant discharge", i.e. a discharge, in which the processes of electron interactions with surfaces play significant role.

## 1. Mass Entrainment

One of possible limitations on ion source operation is existence of the background pressure in the vacuum facility. It happens due to several reasons. As a rule, most vacuum chambers are equipped with insufficient power pumping means. It usually shows, when ion source begins operation at a maximum performance (high discharge currents low discharge voltages) that requires high mass flows of a working gas. As a working gas mass flow increases, the vacuum pumps become unable to properly absorb a large working mass flow. In result, the vacuum background pressure begins increasing. The increased mass flow changes an ion source normal operation. Another possible disruption of normal operation is insufficient pumping after a vacuum chamber opening and closing. It is a known fact that some customers, due to certain business requirements, are trying to reduce the pumping to an unacceptable short time. Here follows another problem with entrapment of water vapors and insufficient evacuation time of water vapors, leading to a significant restructuring of discharge conditions and a corresponding non-standard operation. All these factors, working gas mass entrainment and water vapors entrapment substantially change the operation conditions. However, if water vapors can be extracted after adequate pumping (all this depends on pumping means and pumping time), the mass entrainment would stay high in most cases at the maximum operation conditions.

As it described in our previous publications [1, 3] water vapors together with discharge restructuring usually introduce strong oscillations and instabilities that disrupt normal ion source' operation.

At the same time, working gas entrainment usually does not change drastically an ion source operation, but this effect changes the operation parameters from those given in the manuals. As a rule, excessive entrainment increases the ion beam current and "smears" the ion energy distribution, in some cases, resulted in unexpected higher ion beam current values.

Therefore, in order to provide confidence in operational characteristics, it is desirable to have background pressures with the minimum entrainment effect.

In one of our publications about the facility effects on electric propulsion de-

vices, which are quite similar in operation in many aspects to ion sources, the entrainment effect is discussed in details [4]. The background gas entrainment is considered as the result of a random flux of background gas molecules through the ion source' exit end side. Assuming that during an ion source operation there is performed the free molecular flow condition (which is in fact true for practically all ion sources), the background gas flow can be modeled by the following equation [5]:

$$\Phi = (1/4)n_b(8kT/\pi m)^{1/2} = P/(2\pi mkT)^{1/2}, \quad (3)$$

where  $\Phi$  is a random particle flux across an ion source end-side surface;

$n_b$  is a background gas number density;

$m$  is a background gas molecular weight;

$T$  is a background gas temperature;

$P = n_b kT$  is a background gas pressure.

The background entrained gas mass flow  $\dot{m}_{en}$  is the random thermal flux of molecules at the ion source exit plane integrated over the ion source end side area:

$$\dot{m}_{en} = \Phi m A = m^{1/2} A P / (2\pi k T)^{1/2}, \quad (4)$$

where  $A$  is an ion source exit area.

In **Figure 1** there is shown the entrainment mass flow rate ratio of entrained to anode mass flow  $\dot{m}_{en}/\dot{m}_a$  is shown for the ion source discharge chamber and for the Hollow Cathode.

For the conditions with operation of gridless ion sources our estimations show that because the typical mass flow measurements uncertainties are approximately of a few percent, the entrained mass flow rate should be about 5% or less of the anode mass flow rate, and such entrainment mass would be in general acceptable for gridless ion sources operation.

However, in some cases, even larger entrainment may happen, especially with small vacuum chambers and insufficient pumping means. For each technological process it is necessary to make estimation of impact of the entrained mass flow. In general, for most technological processes the background pressure should be better than  $5 \times 10^{-5}$  torr.

## 2. Charge-Exchange Influence on Ion Beam Flow

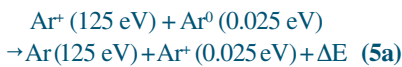
The high operational pressures in vacuum chamber can produce quite a significant effect on ion beam propagation through the

distance for interaction with the target. The propagation of energetic ions through a gaseous medium gives rise to a numerous types of collisions, such as excitation, ionization, charge, momentum and energy transfer. One of such collisions, when during interaction between particles there takes place exchange of charges is called a charge exchange. During such interaction, an ion passing near atom takes away from a neutral particle its electron, preserving its velocity and direction of motion. During the exchange of charges a fast ion becomes a fast atom and a slow atom becomes a slow ion according to the scheme:



Charge exchange of ions on atoms of the same gas also called the resonance charge exchange (like  $Ar^+$  and  $Ar^0$ );  $\Delta E$  is usually a small amount of energy released during such a process.

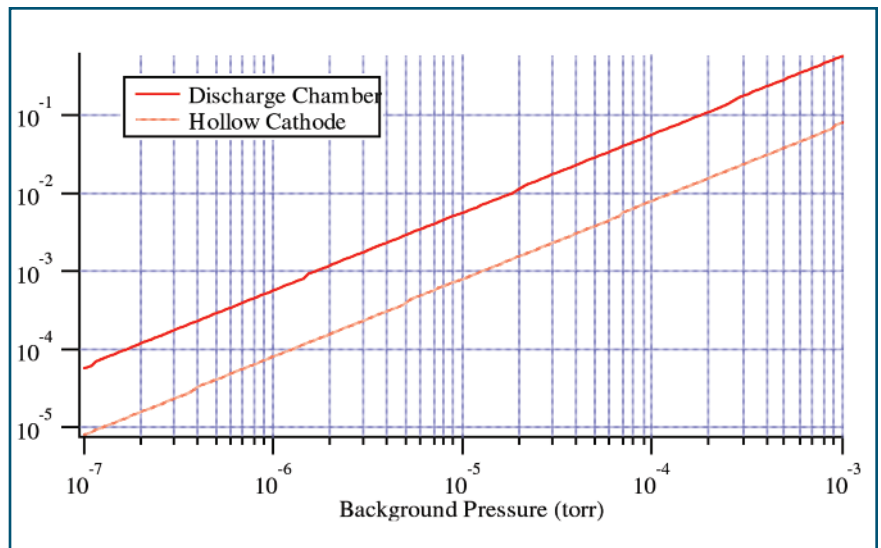
The reaction (5) also can be expressed in more familiar terms, taking into account the fact that low energy neutral atoms have room temperature, which is equivalent of 0.025 eV, and energetic ions with energy of, for example, equal to 125 eV:



The developed low-energy ions, in general, are far from anode and can not be accelerated to the total anode potential. This process leads to expansion of ions energy distribution.

The nonresonant reactions take place between the ions and neutral particles of different species (like  $Ar^+$  and  $O_2$ ). The cross sections of the nonresonant reactions are about an order of value smaller than those for the resonant reactions. The mean free path for the resonant charge exchange reaction is usually an order of value shorter than the momentum exchange, the most significant collisional process.

The charge exchange process at high pressures in vacuum chamber of about  $5 \cdot 10^{-4}$  torr and up (\*reminding to gridless ion source users: the typical pressure range of operations is from about  $5 \cdot 10^{-5}$  torr and up to about  $2 \cdot 10^{-3}$  torr) makes the ions distribution substantially more diffuse after moving from an ion source exit plane. Slow background neutral particles appeared in result of charge exchange reactions diffuse



**Figure 1.** Ratio of entrained mass flow to anode mass flow rate  $\dot{m}_{en}/\dot{m}_a$  as function of facility background pressure; xenon is working and background gas

isotropically from the point of the reaction. At the same time, fast ions transformed into fast neutral particles with their momentum practically undisturbed. The ion beam current that was at the ion source exit plane now is redistributing from the ion source centerline to high angles with respect to the ion source axis.

The ion beam current density as function of distance from an ion source exit plane can be obtained from the ion particles continuity equation. For the steady, one-dimensional flow field with the charge exchange reaction the fast ion continuity equation has the following form [1]:

$$\partial(n_i v_z)/\partial z = -n_b n_i \sigma v_z \quad (6)$$

where  $n_i$  is an ion beam density of fast ions;  $v_z$  is a relative velocity of particles;  $\sigma$  is a resonant charge exchange cross section;  $n_b$  is a background particles density;  $z$  is a distance from an ion source exit plane along the source's axis.

The ion current density decreasing due to the charge exchange reaction at the point  $z$  from the ion source exit plane is expressed by a simple formula [6]:

$$I = I_0 \exp(-n\sigma z), \quad (7)$$

where  $I_0$  is the ion current density at the ion source exit plane. To rewrite this equation for the ion current density in terms of pressure, substituting density from the formula:

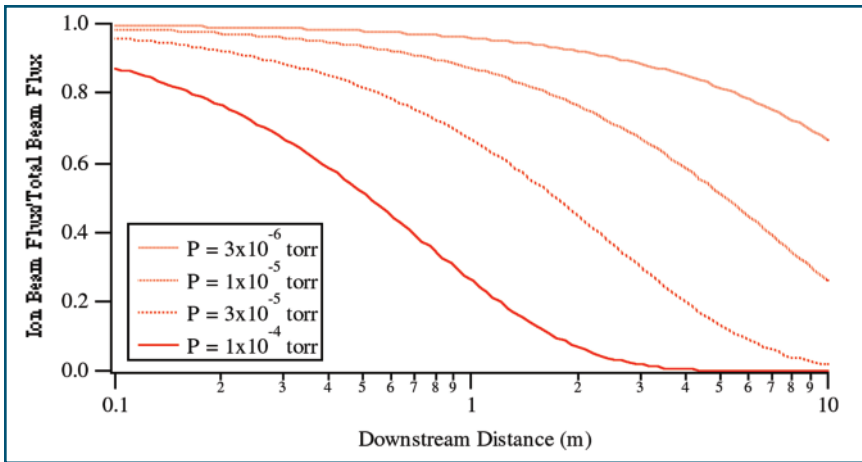
$$p = nkT, \quad (8)$$

and substituting the Boltzman's constant  $k$  and temperature  $T$  equal to 293 K, one can write the equation (7) as

$$I = I_0 \exp(-3.3 \cdot 10^{16} p \sigma z). \quad (9)$$

After utilizing the resonant charge exchange cross section it is easy to obtain the dependencies of the relative attenuation of an ion beam current. In **Figure 2** there are presented the curves for the attenuation of the ratio of the ion beam current to the ion beam current as function of distance from an ion source exit plane for several background pressures; working gas xenon with the background temperature at 293 K; ion beam mean energy is 200 eV [4]. The xenon charge exchange cross sections are:  $4.0 \cdot 10^{-15} \text{ cm}^2$  for  $E_i = 270 \text{ eV}$ ;  $4.2 \cdot 10^{-15} \text{ cm}^2$  for  $E_i = 200 \text{ eV}$ ;  $4.8 \cdot 10^{-15} \text{ cm}^2$  at  $E_i = 70 \text{ eV}$  [7]. For argon the charge exchange cross sections [6] are:  $3.1 \cdot 10^{-15} \text{ cm}^2$  for  $E_i = 100 \text{ eV}$ ;  $3.0 \cdot 10^{-15} \text{ cm}^2$  for  $E_i = 200 \text{ eV}$ ;  $2.2 \cdot 10^{-15} \text{ cm}^2$  for  $E_i = 300 \text{ eV}$ .

It is necessary to note that at lower than 50 eV ion energies the charge cross sections are increasing approximately linearly with energy. This important fact should be taken into account. Because, due to recent tendencies in thin film technology to use low energy ion beams that are lower than a so-called sputtering threshold, which is usually between 15-50 eV for most materials, low ion beam energies are mainly achieved by a high rate of working gas mass flow leading to high background pressures of about  $(1-2) \cdot 10^{-3}$  torr. And at such pressures the charge exchange process will be very no-



**Figure 2.** Attenuation of the ion beam current caused by charge exchange process as function of distance from the ion source exit plane for various background gas pressures; xenon; ion beam mean energy  $E_i = 200$  eV; curves go up from high to low pressures

ticeable at distances over 15-20 cm from the ion source.

These considerations should be taken into account in certain specific cases, if necessary to control an ion beam with magnetic, or electric fields, or for those who measures exact ion beam current value and estimates its impact quantitatively on the sputtering, etching, interaction with a biased target, or a substrate, etc. However, and many cases, in the production it may not be a very important issue at all, because the charged exchanged neutral atom with the same high energy that ion will produce the same necessary “damage” to a target, or a substrate. Still, the spread for an ion beam and its energy in some cases can be important.

### 3. Double Ionized Particles and Their Roles

Double ionized particles can be developed in ion sources usually at high discharge voltages of about 200 V and higher. However, in certain cases, when in electrical discharge there is applied a high concentration of energy in a small volume, it is possible to expect to observe double ionized particles at much lower discharge voltages, even at  $V_d = 20-30$  V, when ions are generated without two missing electrons. The impact of double ionized particles can be important in the cases, when it is necessary to avoid sputtering target at higher energy and surfaces surrounding target than the designed energy.

For example, in the recently developed technology of a thin film deposition by a so-called biased target deposition [22, 23] this can be important even at very low ion beam energies of 20-30 eV. In this case, when it is

necessary to have a very “pure” ion beam of a working gas without any contaminants, an ion beam energy applied to a target must be lower than a sputtering threshold energy of the surrounding biased target parts in a vacuum chamber and chamber itself, so these sputtered particles would not contaminate the main process from a target.

Another example. In the case of sputtering of certain material by an exact ion beam energy particles, it is desirable that the sputtering ions would produce exact number of particles at certain energy. Presence of double ionized particles with double energy of these ions can confuse the process, making it uncertain even with a very low percentage of double ionized particles.

Fast ions (with energy higher than single ionized particles) bombarding target and its surrounding can be developed during the main ionization process in discharge characterized with high density of heat release in a small volume (for example, in a high-current Hollow Cathode, or a high power ion source with relatively small discharge chamber) even at low discharge voltages of 20-30 V.

Because an ion beam is formed in discharge plasma, and in case, if in discharge there were developed multi-charged ions, these multi-charged ions can participate in the ion beam flow traveling outside the discharge channel. At a certain value of the ion mean energy  $\Delta\varphi$  the kinetic energy of ions with an ionization multiplicity  $z_i$  is equal to  $E_i = z_i e\Delta\varphi$ , i.e. it is  $z_i$  times bigger than energy of usually taking into account single-charged ions. For the ions with  $z_i > 1$  the probable threshold energy of sputtering is decreasing in  $z_i$  times.

Besides that, it is necessary to take into account that at  $E_i \approx E_{i,th}$  (threshold sputtering energy) the sputtering coefficient is a sharp function of ion energy. For example, the increase of  $E_i$  in two times, which is the characteristics of double-charged ions, gives in certain cases the increase for the sputtering coefficient in  $10^3-10^4$  times. That is why the presence of even small portion of double-charged ions in ion flow (about  $10^{-3}-10^{-4}$ ) significantly increases the sputtering coefficient  $Y_0$ . Thus, the ions with  $z_i > 1$ , even if they do not produce any influence on the balance of current and energy in the discharge process, they can substantially impact on a sputtering process. For example, a noticeable sputtering at  $e\Delta\varphi < E_{th}$ , i.e. lower than the sputtering threshold for ions with  $z_i = 1$  can be observed at the ratio of double-charged ions to single charged ions  $\gamma = \Gamma_2/\Gamma_1 \approx 10^{-3}$  (Figure 3.) [8].

During the analysis of influence of ion beam energy on sputtering of various materials it is also necessary to take into account the specific conditions of sputtering depending on the ion beam mass composition, the energy distribution of particular ion beam, and the target’s temperature.

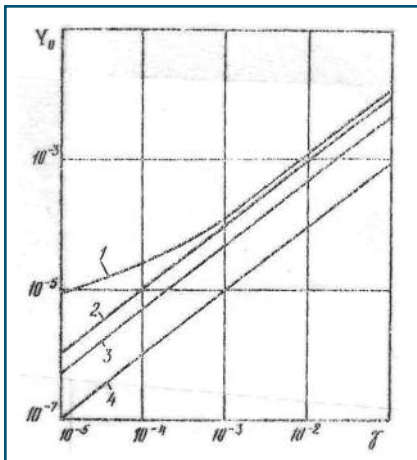
Ions in ion beam have a certain energy distribution. An ion beam of a gridless ion source is not a monoenergetic beam. It is usually characterized by the mean ion energy that is for different types of gridless Hall-current ion sources is varied from  $E_i \approx (0.6-0.8) \cdot V_d$ , where  $E_i$  is expressed in eV. However, in the ion beam energy distribution (see, for example, our article “Optimum Operation of Hall-Current Ion Sources” in [3], Figure 7 with  $V_d = 150$  V, where together with the  $E_i = eV_d$  there are ion energies up to  $E_i = 190-200$  eV), there are ions that have energy higher than the mean and maximum energy of  $eV_d$ .

Also, besides the presence of double ionized particles during an ion source operation, especially at high discharge powers a target can become heated by incoming beam and the target’s temperature can change the sputtering coefficient significantly.

In Figure 4 there is shown the dependence of the sputtering coefficient  $Y$  as a function of Argon ion beam energies ( $E \leq 300$  eV) for interaction with a Tungsten target at different target temperatures.

As one can see, the sputtering coefficient is highly dependent of a target’s temperature.

Here is the conclusion about the double



**Figure 3.** Average sputtering coefficient  $Y_0$  of Tungsten electrode as function of portion of double-charged ions ratio of Xenon  $\gamma$  at different values of  $e\Delta\phi$ . Curves: 1 -  $e\Delta\phi = 1.04E_{th}$ ; 2 -  $e\Delta\phi = E_{th}$ ; 3 -  $e\Delta\phi = 0.83E_{th}$ ; 4 -  $e\Delta\phi = 0.7E_{th}$

ionized particles. For certain fine thin film deposition processes it is necessary to take into account the double ionized ions. However, for some sputtering and etching tasks presence of double ionized particles can be negligible.

#### 4. Impact of Vacuum Chamber Pumping Rate

The technology of deposition of optical films by the electron beam evaporation with ion assisting usually provided by processing of growing on substrate thin film with an oxygen ion beam, or some other gas with the purpose to help obtaining the properties that impossible to deliver by a simple heating of a substrate's surface. Some improvements in ion assisted film deposition include such features, as increase of adhesion and film density, decrease of optical absorption with corresponding increase of stability of the film's optical properties. Majority of modern thin film deposition vacuum chambers have vacuum pumps with pumping rates of 500-5000 l/s.

However, the utilization of vacuum pumps with higher pumping rates is quite desirable in order to provide better stability of the ion source operation. In the last 15 years there were actively developed thin film depositions of Tantalum, Hafnium, Niobium, Titanium and other oxides through evaporation of corresponding metals by electron beam in presence of ionized oxygen. For these particular elements oxides the growing substrate becomes a getter

for oxygen, i.e. as the additional pump that pumping rate added to the main vacuum pump. With the change of the evaporation rate by electron beam there is changed the pumping rate of the additional pump, which produces a certain negative impact on the stability of the ion source's operation.

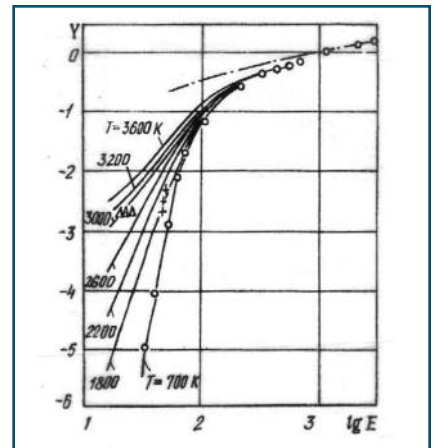
In such a case, the higher rate of pumping of the main pump, the less impact will be introduced by the additional pumping caused by the getter-effect of a growing film. Since many vacuum chambers for industrial thin film depositions are not equipped with powerful pumps, and with the purpose of maintaining the same discharge and correspondingly ion beam current, it is usually done with the change of the working mass flow through an ion source.

According to [11], in the vacuum chamber "Leybold" equipped with cryopumping evacuation provided an oil-free vacuum of better than  $3 \times 10^{-7}$  torr during thin film deposition with electron beam evaporation and ion assist of end-Hall ion source with oxygen with about 60 sccm of mass flow. However, when the process is in operation for several hours (6 hours and more) the pressure in vacuum chamber was decreasing from about  $3 \times 10^{-4}$  torr to about  $1 \times 10^{-4}$  torr. In this case, in order to maintain the operating parameters of discharge current, it was necessary to apply more working gas flow into end-Hall discharge channel by almost two times.

#### 5. Dielectric Depositions on Anode During Operation with Reactive Gases

During operation of ion sources with reactive gases either as working gas, or additional gas applied into the deposited area the development and deposition of poorly conducting coatings on ion source discharge channel, and, especially, on anode can bring very unpleasant effects in operation. Such coatings can be developed from various sources.

Residual gas molecules in vacuum chamber other than the background working gas molecules are typically composed of oxygen, nitrogen, water vapors, various hydrocarbons as result of vaporization of diffusion and mechanical pump oil, and vacuum chamber openings. These residual gases can be absorbed on the surfaces of ion source, especially on anode, and develop various di-



**Figure 4.** Dependence of sputtering coefficient  $Y$  of Ar ion energy  $E$  at different temperatures of target (W): — calculation [9]; — · — calculation according to Sigmund's cascade theory [10]; o, +,  $\Delta$  - experimental points

electric depositions. These depositions can produce substantial impact on the ion source operation.

This effect, sometime called as anode "poisoning", presents huge problem for the thin film deposition processes with reactive gases. This problem and how it can be solved for the end-Hall and closed drift ion sources needs special analysis and will be considered in our next publications in VT&C. However, here we will discuss shortly what to do during regular operations and in the cases, when dielectric depositions produce occasional impact on the ion source work.

The accumulation of poorly conducting or nonconducting coatings on the anode during operation in an adverse environment presents an inherent limitation of the ion sources. The most common solution for elimination of such coatings is maintenance, i.e. disassembly, cleaning or replacement of components covered with dielectric depositions. In both examples, when the discharge voltage went up, an ion source operated with a Power Supply in the constant discharge current mode. In the regime with a Power Supply operating with a constant discharge voltage mode the discharge current decreases. However, such maintenance and substitution of components interrupts production and increases costs.

From the author's experience with thin film depositions, especially nasty for the ion source operation are  $SiO_2$ ,  $Al_2O_3$ ,  $Ta_2O_5$  and few others.

**Example 1.** After beginning of the thin film deposition process with end-Hall ion source at certain discharge voltage of

$V_d = 30\text{--}35\text{ V}$  and at the discharge current  $I_d = 7.5\text{ A}$  with working gas oxygen, the oxygen ions bombard a Tantalum target that is at a biased potential of  $-500\text{ V}$  (relative to a vacuum chamber's ground). Tantalum particles move under influence of electric potential and directed to the deposition substrate. In the first 2 hours of ion source operation the discharge voltage gradually increases by about  $10\text{ V}$  and in the next several hours the discharge voltage increases by another  $7\text{--}8\text{ V}$ .

**Example 2.** The deposition of  $\text{SiO}_2$  leads to even more drastic change of the discharge voltage. In order to continue normal deposition it is necessary to clean anode regularly after every 2 hours of operation.

There are several methods of how to improve the ion source operation during deposition of oxides and other dielectric materials. One of the most radical ways to eliminate such anode "poisoning" is to redesign the end-Hall's anode making it in the form of a grooved cone, or install a baffle that can restrict entered sputtered oxides into the anode area [12].

Here are some ways how to operate the ion source in the conditions of dielectric depositions on anode:

1. If the process allows during the each vacuum chamber opening to clean the anode's surface, it should be done on regular basis.
2. After one-two hours of operation, in case, if dielectric deposition would begin producing substantial impact on the operational parameters, in the interval between the processes, or screening the process with a shutter, or simply moving a stainless steel piece between the ion source and the target, it is necessary to increase sharply the discharge voltage  $V_d$  as high as possible. The ion source operating at high discharge voltage will heat the anode and correspondingly will heat the deposited dielectric layer on the anode, and can destroy this deposition, at least, a good part of it (there are no specific experiments on the number or percentage of destroyed depositions). This procedure was successfully used with various oxide depositions and helped temporarily to eliminate dielectric depositions and to continue the operation process.

## 6. Estimation of Returned Sputtered Particles to Ion Source

Besides deposition of dielectric materials

on ion source surfaces during utilization reactive gases there exists a deposition process of exposed ion source surfaces from sputtered materials coming from the vacuum chamber and other parts and details that always present in vacuum chamber. Such deposition is the result of high energy ion beam ( $> 50\text{ eV}$ ) interaction with vacuum chamber walls [13]. Together with sputtering of vacuum chamber walls there is also erosion of ion source's discharge channel parts caused by ion beam.

In **Figure 5** there is presented the model of a vacuum chamber walls sputtering due to ion beam developed by an ion source [4]. The average rate of sputtered material returned into the ion source can be described by the expression:

$$\delta = (1/a) \int_a \xi [(\cos\alpha \cos\beta) / \pi r^2] dA \quad (10)$$

where  $a$  is an ion source surface area;

$A$  is a vacuum chamber surface area;

$\xi$  is a local sputtering rate;

$r$  is a distance between a vacuum chamber wall and ion source;

$\alpha$  is an ion source normal angle with  $r$ ;

$\beta$  is a vacuum chamber wall surface normal angle with  $r$ .

This expression can be transformed into analytical form for a circular disc perpendicular to the ion source axis with the integral equal to

$$H = \int_a \xi [(\cos\alpha \cos\beta) / \pi r^2] dA \quad (11)$$

For a narrow circular ring perpendicular to the ion source axis, where  $\xi = \text{constant}$ , the equation (11) can be expressed in the form:

$$\delta_i = \xi_i H_i / a, \quad (12)$$

$$H_i = H(D_{2i}) - H(D_{1i}), \quad (13)$$

where  $D_{2i}$  and  $D_{1i}$  are the external and internal diameters of the ring, correspondingly. The integral of equation (11) is expressed in the analytical form in [14], and in the sim-

plified form it can be written as:

$$H \approx \{(D/L)^2 / [1 + (D/L)^2]\} / a. \quad (14)$$

The sputtering rate of the vacuum chamber wall material is determined by the well-known expression

$$\xi = S_{\beta} j \cos\beta, \quad (15)$$

where  $j$  is the ion beam current density at the ion source exit plane;  $S_{\beta}$  is the volumetric sputtering yield.

The current density change as function of distance from the ion source without taking into account a charge exchange effect and in a collision-free molecular flows is expressed by the point approximation:

$$j \approx j_0 r_0^2 / r^2. \quad (16)$$

One of examples of the ion beam current density is given in [15]. And the volumetric sputtering yield for the metallic materials is determined from the following expressions:

$$S_{\beta} = (AE + B) / \cos\beta \quad \text{for } \beta < 60^\circ \quad (17)$$

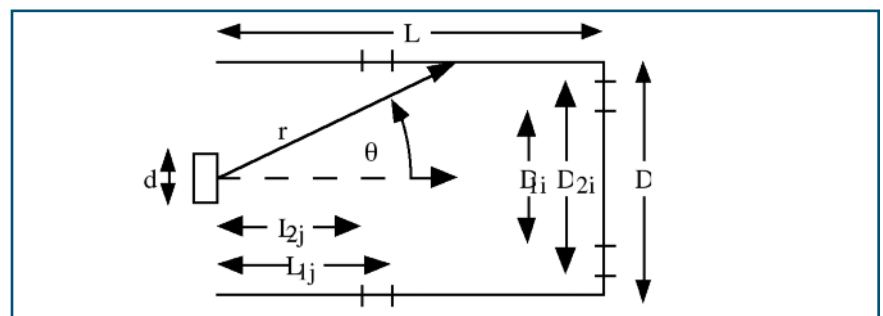
$$S_{\beta} = [(AE + B) / \cos 60^\circ] [(90^\circ - \beta) / (90^\circ - 60^\circ)] \quad \text{for } \beta \geq 60^\circ$$

where  $E$  is the ion energy;  $A$  and  $B$  are the linear fit coefficients.

The ion energy is calculated from experimental data. The total deposition rate can be calculated after summation of the sputtering contributions from all rings:

$$\delta_{\text{total}} = \sum_i \delta_i \quad (18)$$

Deposition rates calculated with equation (18) are given in **Figure 6** for several ratios of the vacuum chamber length  $L$  to the diameter value  $D$ , or  $L/D$ . These sputtering rates have been calculated for the stainless steel walls. As one can see, the variation of  $L/D$  ratio does not produce significant impact on the sputtering deposition rate. For the constant value  $L/D$  the deposition rate is inversely proportional to the vacuum chamber length, or



**Figure 5.** Schematic picture of vacuum chamber walls sputtering

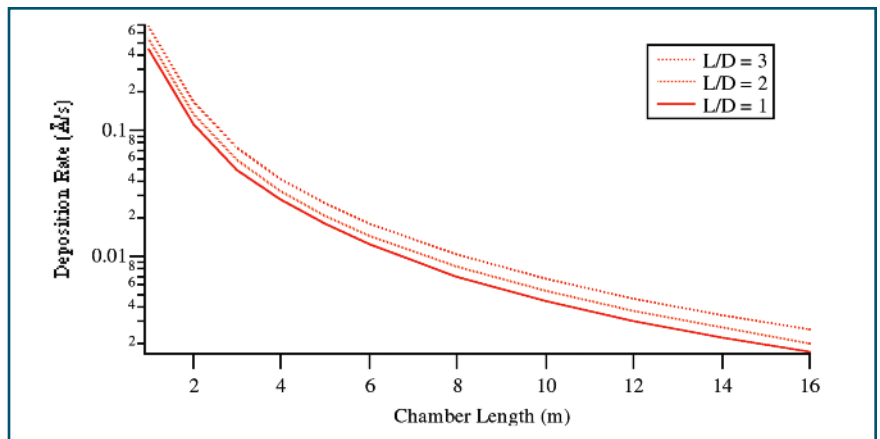
$$\delta \propto 1/L^2. \quad (19)$$

Due to the fact that in equation (16) there is no dependence on length for a constant L/D, the deposition rate as function of L is determined by the decreasing current density according to equation (16). In result, the sputtered rate return rapidly decreases with the longer vacuum chambers.

For the processes, where it is necessary to have quite pure thin film depositions without much influence from an ion beam sputtered return there are used various baffles and vacuum chamber walls get covered with low sputtered rate material.

The baffle effect provides the reduction in sputter yield caused by the very high incident angles of the ion beam flow with respect to the baffle surface normal, and the reduction in view factor from material sputtered from the baffle surfaces. The baffle utilization can reduce the sputtered return by a factor of 1.2-2.2. Since in thin film technology there are utilized comparatively short vacuum chambers of 1-1.5 m long and about 0.5-1.0 m in diameter in comparison with electric propulsion facility tests the returned sputtered material deposition rates can be noticeable from 1 to 5-7 Å/s. Simple calculations show that for the returned sputtered deposition during the process taking place in some optical precision making thin film depositions, for example, with the returned sputtered deposition of 5 Å/s during 6 h of operation one can have on the ion source about  $1.8 \cdot 10^{-4}$  cm. This value should be taken into account seriously.

Another important consideration together with the entrained mass flow and returned sputtered deposition particles into an ion source is a selection of vacuum chamber adequate dimensions. A vacuum chamber dimension is especially important for tests with electric propulsion devices, when it is necessary to simulate the conditions close to space with high vacuum and not so many spacecraft parts (spacecraft itself and solar panels could be some problems) that can be sputtered by an ion beam and reflected back to a thruster. For such experiments of thruster's space simulation usually there are selected quite large vacuum chambers with a high ratio of a vacuum chamber area to a thruster's exit area. Vacuum chambers for thrusters are real big installations and very expensive, because they must be well pumped to a high vacuum ( $10^{-8}$ - $10^{-7}$  Torr). There are known several unfortunate cases,



**Figure 6.** Calculated sputtered return material deposition rates  $\delta$ , Å/s as function of a vacuum chamber length L, m with various ratios of a vacuum chamber length to its diameter, stainless steel walls

when a university or a private laboratory bought a large vacuum chamber of about 3-5 m long and about 2 m diameter, and after successfully (or not) finished experiments could not use such vacuum chamber anymore, because it is very expensive to pump such a chamber and its opening-closing takes quite a long time to achieve necessary experimental conditions (1-2 hours).

For the ion sources of moderate power with usually radiation cooled ion sources that consume about 500-800 W, and water cooled ion sources with 1.5-3 kW, it is not necessary to have a big vacuum chamber. But such a chamber still needs to be of a reasonable size (not too small), so that sputtered and entrained particles should not play detrimental role influencing on a stable ion source operation and would not influence significantly on the thin film technological process. For the Hall-current ion sources that have exit source's part of 5-10 cm in diameter, the dimensions of exit area should be at least with the ratio of a vacuum chamber exposed to an ion source by sputtered particles to an ion source exit area, or about 100:1. That ratio will be well satisfied with a vacuum chamber of about 1-1.5 m in diameter and about 1-1.5 m of length. This dimension is easy to pump and can provide adequate experiments with operation pressures from about  $10^{-5}$  to about  $(1-2) \times 10^{-3}$  Torr with the preliminary pumping to about  $10^{-7}$ - $5 \times 10^{-7}$  Torr. Also, such a dimension gives sufficient room for placement various targets, substrates and measurement probes.

Unfortunately, the author have met, and not once, some laboratories that had vacuum chambers of dimensions of about (30-40)×(30-40) cm, which produced signif-

icant impact on the ion source operation with high entrained working gas mass flow and high deposition of sputtered particles into a Hall-current ion source discharge channel.

To reduce a flow of sputtered particles into a discharge channel area from a vacuum chamber walls it is prudent to have a usually stainless steel vacuum chamber's interior surface be covered with a low sputtering material, such as graphite in operation with noble gases, or with an Aluminum foil in operation with Oxygen that is in a very short time (a couple of hours) becomes covered with an Alumina layer, which is a low sputtering material. A vacuum chamber surface in many cases in the thin film deposition process plays so important role that its proper selection is one of the most important factors in successful thin film deposition process.

Besides all above mentioned factors, one of the most frequent mistakes in operation is fast vacuum chamber opening and insufficient vacuum chamber pumping after its closing. Fast opening leads to sharp change of temperature conditions that can lead to degradation of some in chamber parts, like targets, substrates, and an end-Hall magnet, which after fast opening increases its temperature in the first 1-2 minutes sometime by about 100 C over the operation temperature. For certain magnets such sharp increase leads to the magnet's degradation and demagnetization, in some cases, irreversible.

Fast insufficient pumping in many cases does not allow time for removal major vacuum chamber's contaminant – water vapors. Experiments with various end-Halls and closed drift ion sources showed that short time pumping (10-15 minutes) leads to

very unstable operation of ion sources with wide varieties of unpredicted parameters: insufficient ion beam current value, large ion beam energy smear, large range of discharge voltage and current oscillations with transitions into instabilities and discharge interruptions.

Among all pumping means the cryopumps (expensive) are the most advisable for utilization in operation with ion sources, because they are clean, fast and have no oil. Diffusion pumps (though they are cheap) are the most undesirable with the ion sources. Long practice with diffusion pumps in Russian Electric Propulsion test chambers showed that oil residues have a tendency for accumulation in the closed drift thruster-ion source discharge channel, especially in the anode area, leading to unexpected change of operation conditions increasing the level of discharge current and voltage oscillations. The same effect takes place with end-Hall ion source. Hydrogen and oxygen contaminants "poison" anode and shift operation conditions forcing to frequent anode cleanings, or modifying anode, or discharge channel design [12]. Some good information about selection of a vacuum chamber can be found in [16].

## 7. Influence of Ion Source Heating on Its Operation

The ion sources such as Mark-1, Mark-2, EH series, and other producers can be a radiation, or water cooled (water, or any other fluid is applied into anode, or other parts of ion source [17]). More than this, some ion sources are equipped with water cooled front plates [18], water cooled magnets [11, 19], some vacuum chambers have water cooling walls. Water cooled versions are usually do not change ion sources operation parameters substantially during several hours of continuous operation. Existing radiation cooled versions can change the operation parameters, if the ion source operator would apply the power higher than it is in the design. For example, the end-Halls EH-200, EH-400 (all of them are radiation cooled) can sustain the applied power of about 200 and 400 W, or Mark-2 (in the radiation cooled version) can sustain the power of about 850 W. The users must make simple calculations of the discharge current and voltage and not to go over those powers.

Since in the majority of end-Hall ion sources the main magnet is placed along the ion source's axis and is protected from the direct plasma flow by a so-called reflector

gas distributor, it can be heated to quite high temperatures of about 500 C. The ion sources of main end-Hall producers *Veeco* and *K&R* have their magnets made of Alnico-5, or Alnico-8. These magnets have a high working temperature limit of 550°C with good resistance to demagnetization and stability due to its low temperature coefficient of demagnetization 0.02% for each degree of Celsius.

However, some end-Hall producers use magnets of rare-earth materials that lose magnetism quite fast with heating over 300°C. In result, the ion sources with low magnetic field change the operational characteristics (usually end-Halls with low magnetic field can not achieve high discharge voltages at high discharge currents [19]) and users have serious problems, because in certain thin film deposition processes even small changes of an ion beam current and ion energy can cause substantial changes in films optical properties.

## 8. Negative Ions and Their Role

Here is another approach to the internal depositions on an ion source's discharge channel.

In [2] there is developed a theory and provided experimental proof of existence of negative ions in vacuum chamber during operation of the ion source-thruster.

The ionization cross sections for Ar atoms [positive ions of a secondary plasma developed in vacuum chamber cannot come into an ion source discharge channel due to a presence of electrical field E] are:

$$\begin{aligned}\sigma_{\text{ion}} &= 2 \times 10^{-16} \text{ cm}^2 \text{ at } T_e = 20 \text{ eV; and} \\ \sigma_{\text{ion}} &= 4.7 \times 10^{-16} \text{ cm}^2 \text{ at } T_e = 40 \text{ eV;}\end{aligned}$$

and a charge-exchange cross section

$$\sigma_{\text{ch-exch}} = 4 \times 10^{-15} \text{ cm}^2$$

for ions with energy about 300 eV on non-moving neutral particles. From here follows that a mean free path of a neutral particle (located outside a discharge chamber) for ionization:

$$\lambda_{\text{ion}} = v_0 / (n_i \langle \sigma v \rangle) \sim 1 \text{ cm,}$$

and a mean free path of a charge-exchange particles is:

$$\lambda_{\text{ch-exch}} = v_0 / (n_i \langle \sigma_{\text{ch-exch}} v_i \rangle) \sim 2 \text{ cm.}$$

Here  $n_i \approx n_e$ ,  $v_i$  corresponds to  $E_i = 300 \text{ eV}$ , and  $v_0$  is a velocity of "cold" neutral particles and it is assumed equal to  $2 \times 10^4 \text{ cm/s}$ . From the above given estimations one can see that

neutral particles moving along an ion beam can not come inside a discharge channel, because they will be rapidly ionized and thrown away by a positive flow potential. In reality, neutral particles can "get in" from the side, at the source entrance end-side.

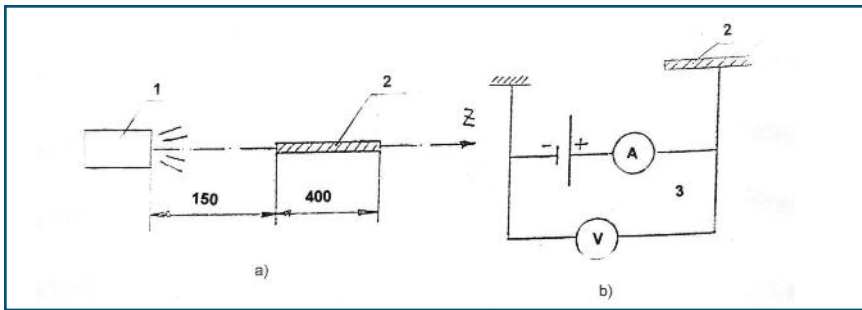
Experiments show that the ion source discharge channel is covered with different depositions (depending on kind of "work"). One can get an impression that the sputtered particles are "attracted" into an ion source discharge channel. A presence of deposited layer from sputtered metal testifies that there is a well focused flow of metal ions coming from a vacuum chamber into a discharge channel. All these facts permit to assume that *a flow of negative ions developed on the surface of a target (and a vacuum chamber) comes from a vacuum chamber into a discharge channel*. Such a flow of negative ions, due to a main beam's flow positive potential is transported to the ion source's exit part and into the discharge channel.

There were conducted the experiments with the closed drift ion sources of a magnetic layer type [2, 20] with the targets made of materials that do not produce negative ions (Zn, Mn and others). In the experiments with Zn target the vacuum chamber after certain operation time became covered with Zn. At the same time, the internal part of a closed drift ion source was practically clean and the ion source's operational characteristics did not change during many hours (over 20).

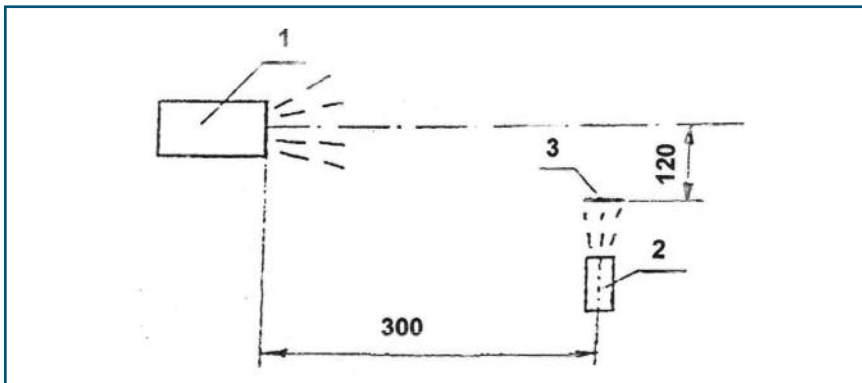
However, Zn or Mn are not good examples as remedies against negative ions, because both elements have very high sputtering rate by an ion beam. There are some other materials, like Hf, Ir and others that do not sputter much and they do not produce negative ions, but they are expensive.

Therefore, one of the simplest methods to fight with negative ions will be a deposition of vacuum chamber walls and a target with a material that does not develop the negative ions. Besides that, there could be other methods to eliminate the negative ions. The main idea is as follows. On the way of negative ions it is necessary to create a potential trap that would capture these ions. For example, a tangential (parallel to an ion source axis) electrically conducting plate having a positive potential can be placed in front of an ion source (Figure 7).

Another method to eliminate negative ions is the utilization of a positive column of glow discharge (Figure 8).



**Figure 7.** Tangential electrically conducting plate with a positive potential for eliminating negative ions directed into a discharge channel: a) 1 – ion source; 2 – tangential plate; b) 3 – electrical scheme for potential application on tangential plate; numbers 150 and 400 are distance and length of a tangential plate in mm.



**Figure 8.** Utilization of glow discharge for cutting off negative ions: 1 – ion source; 2 – glow discharge cathode; 3 – glow discharge anode; numbers 300 and 120 are distances of a glow discharge source and from axis in mm.

Experiments show that the utilization of the traps with the presence of a flow of negative ions leads to the increase of ion beam current by several percent and the ion source's discharge channel is free of depositions.

## Conclusion

The ion source operation in the vacuum chamber is quite a complex system. The physical processes discussed above such, as the charge exchange at higher pressures, possible presence of double ionized particles, dielectric and conducting depositions in the discharge channel, inadequate vacuum chamber dimensions, wrong covering of its internal surface, heating of the discharge channel and target, insufficient pumping means, presence of the negative ions have to be analyzed for each particular thin film technology task.

All these factors must be taken into account for optimum performance.

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