CATHODES-NEUTRALIZERS FOR ION SOURCES

PART 1

Introduction, Hot Filaments

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This article "Cathodes-Neutralizers for Ion Sources" consists of 3 parts. Part I published in this issue is "Introduction" and "Hot Filaments". Part 2 is about "Hollow Cathodes". Part 3 Plasma Bridge, RF-Neutralizers, and others.

Of the most important problems that broad beam industrial ion sources users face every day during operation of Hall-current ion sources, such as end-Halls, Closed Drift of Magnetic and Anode Layer, and other types, is the cathode lifetime, simplicity, reliable operation and cost. Because the industrial ion sources produce the low-energy ion beams and operate in a so-called non-self-sustained discharge regime [1], they require existence of external source of electrons for ionization and neutralization of a space charge and an ion current. It is necessary to provide a certain value of electron emission from a cathode-neutralizer to eliminate extra positive charges from surfaces near or in an ion beam, especially, on surfaces of targets and deposition substrates. Ion sources users that manipulate an electron emission from a cathode-neutralizer in order to eliminate visible sparks produced by insufficient number of electrons operate with a cathode-neutralizer and this is called a ***charge neutralization*** of ion beam. However, the best results in thin film deposition technique is provided by a ***current neutralization*** that is achieved by having a cathode-neutralizer emission current equal to an anode discharge current.

1. ION BEAM AND ITS NEUTRALIZATION

It is necessary to clarify the situation with ion sources that were analyzed in our previous *VT&C* articles [1-9]. In these publications Hall-current ion sources of the so-called Closed Drift of Magnetic and Anode Layer and the end-Halls are the main industrial ion sources used by over 90% of world gridless ion sources users. These ion sources deliver ion beams of many working gases such as Oxygen (about 70-75% of all industrial applications), Argon (10-15%), Nitrogen (5-10%), Xenon (1-2%), Hydrogen (less than 1%), other gases (about 5%). The ion sources discharge voltages are from about $V_d = 50$ V to about 500 V. These voltages in Hall-current ion sources correspond to the mean ion energies of about $E_i \approx 30$-40 eV to about 300-400 eV. The discharge currents are usually from about $I_d = 0.5$ A to regularly 5 A, though there are recently developed end-Halls with maximum I_d = 10-15 A [10]. These discharge currents produce ion beam currents from about $I_i \approx 0.1$ A to about 2-3 A. There are some exceptions, for example, some Hall current ion sources can operate at V_d = 1000 V [*Closed Drift ion sources] producing ion beams with energies up to $E_i \approx 600$ eV.

However, most ion sources operate in a certain limited range of applied electric powers of not more than 3 kW (water-cooled anodes) and under 1 kW (radiation-cooled anodes). Thus, it is necessary to select the optimum range of ion beam energies and currents for every specific thin film task with the applied electric

power. Of course, there are already Hall current devices made as Electric Propulsion thrusters [*Closed Drift Thrusters that in principle can be the ion sources] for space applications for 50 kW and more, but such devices require large vacuum chambers, powerful vacuum pumps with long pumping, i.e. they are very expensive and certainly impractical for thin film tasks. Modern vacuum systems with Hall-current are of medium dimensions about 50-75 cm in diameter and 75-100 cm long with the ion sources from about 1 to 3 kW.

Most industrial ion sources produce positively charged ion beams, which must be neutralized with electrons. An ion beam leaving an ion source and propagating into a direction of either a target, or a substrate, and into a vacuum chamber and its parts carries a positive electric charge to all these components. This charge in most cases is distributed very unevenly, because the ion current densities in the beam are quite non-uniform and can develop large electric fields in the beam itself and on the surfaces of processing targets and substrates. Insufficiently neutralized ion beams of the broad beam industrial ion sources can have high positive electric potentials sometime of a few hundred volts that produce small sparks and can damage surface of a target and a substrate. In the thin film technology, and especially in the semiconductor industry, many integral circuit components are very sensitive to the electrostatic stress, and can result in a poor uniformity of thin films during sputtering impact with an ion beam. That is why it is necessary to utilize a source of electrons for neutralization of ion beam, and other components such as a target and a substrate depending on arrangement of all these components.

Another purpose of generation of electrons with the ion source is that these electrons present a source of ionization energy of the working gas with lower discharge voltages at a non-self-sustained discharge regime [1], at about 300 V and lower, than without utilization of electron source, when discharge can exist at higher voltages, usually over 300-400 V and up at a self-sustained discharge regime.

After development of an ion beam in an ion source the low energy ions traveling through a certain distance from an ion source experience the condition known as a beam expansion due to the like-charged positive ions that mutually repel each other. This condition is often called also as a space charge effect. The ions mutual repulsion causes an ion beam expansion from an expected desired form; it simply becomes fuzzy. [*There is another physical process that leads to expansion of an ion beam; it is a charge exchange that makes fast energetic ions as fast energetic neutral atoms, or molecules. This phenomenon was discussed in one of our previous publications [2]].

In ion sources with a positive ion beam there are used various devices producing electrons for neutralization of ions in the discharge channel, in the exit flow and for elimination of electrostatic positive charge on a target and substrate surfaces.

There are several methods how to neutralize ions and to prevent an ion beam expansion. The first way is the injection of low energy electrons into the beam, and the second is to reduce electrons leaving or removed from the beam.

For the effective neutralization of ions the electron emission current from a source of electrons must be equal, or greater than the ion beam current. In the case if the electron neutralizing current is less than the ion beam current, the number of ions arriving to the target, or substrate surface will exceed the number of electrons in the same areas, and on the insulating target, or the substrate there will be a positive charge build-up leading to the above mentioned consequences such as sparks damaging processing surfaces. Depending on particular ion sources operation conditions, the electric potentials with the under-neutralized ion beams can be from several volts and up to several hundred volts. The sparks accompanying such positive charge build-up generate electrons that eliminate the excess of ions positive charge. In some cases, even several volts of a positive charge build-up will be sufficient to damage the processing substrate surface [11].

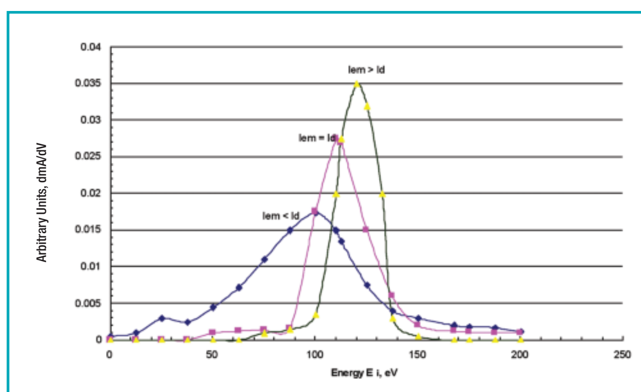

Figure 1. End-Hall new design [12], Ion beam Energy distribution for different neutralization ratios: $I_{em} < I_d$ ($I_{em} = 3.8$ A), $I_{em} = I_d$ ($I_{em} = 4$ A), $I_{em} > I_d$ ($I_{em} = 6$ A) ; $V_d = 130$ V; $I_d = 4$ A; Noble gas [8].

For developers and users of broad beam gridless ion sources it is necessary to emphasize how it is important to have a neutralized ion beam and how underneutralized beam can change drastically major operating parameters, in general, deteriorating them. As examples, in **Figure 1** there are presented typical energy distributions for a new end-Hall type ion source [12] with comparatively monoenergetic ion beam. As one can see, an ion beam with emission current $I_{em} > I_d$, or so called "over-neutralized" beam has the most narrow energy distribution with the ratio of $E_i/eV_d \approx 0.94$; for $I_{em} \approx I_d$ the ratio $E_i/eV_d \approx 0.86$; for $I_{em} < I_d$ the ratio $E_i/eV_d \approx 0.76$. Regular end-Hall ion sources, as it was shown in [1, 3] have $E_i/eV_d \approx 0.6$-0.7. Regular end-Hall ion sources with underneutralized ion beam have the ratio E_i/eV_d substantially lower than 0.6.

In **Figure 2** there are presented Volt-Mass flow Characteristics $V_d = f(\dot{m}_a)$ for $I_d = 1$ A, for different ratios of emission and discharge currents: $I_{em} < I_d$, $I_{em} \approx I_d$ (in fact, $I_{em} \approx 1.1 \cdot I_d$), and $I_{em} > I_d$, working gas Argon. There are several advantages operating with excessive electron emission $I_{em} > I_d$ in comparison with $I_{em} \approx I_d$, which are seen in **Figure 1** and **Figure 2**: 1. an ion beam has a narrow energy distribution; 2. the same discharge voltage with excessive emission needs less working gas mass flow. However, there is a disadvantage: to have a higher electron emission, it is necessary to apply substantially higher heater current to a neutralizer, which means a shorter lifetime of a cathode-neutralizer.

The situation with the ion beam current I_i is very similar to the ion beam energy distribution E_i: higher emission and emission

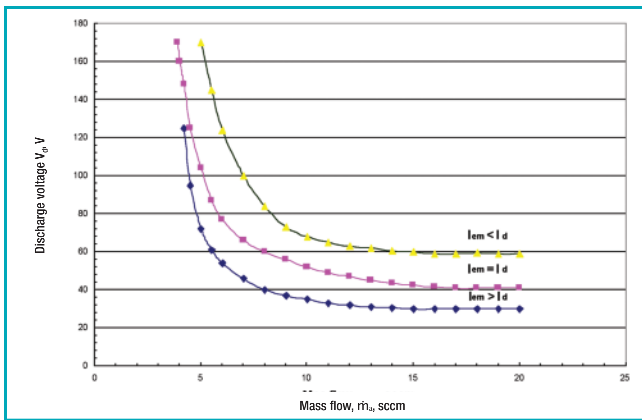

Figure 2. Volt-Mass flow Characteristic $V_d = f(\dot{m}_a)$ for different ratios of emission and discharge currents; $I_d = 1$ A, Argon.

equal to discharge current provide higher ion beam current (this is clearly shown in **Figure 6**, on which an ion beam current is shown by numbers 3 and 4); an under-neutralized ion beam has lower ion beam current and ion beam is more divergent than in two other cases (not shown in **Figure 6**).

In **Figure 3** there is presented a typical picture [13] that shows how electrical potential is varied on electrically isolated target depending on a utilized emission with an ion beam in comparison with the operational discharge current $I_d = 5$ A.

Unfortunately, many ion sources users do not establish correct value of the emission current through the cathode-neutralizer. As it was above mentioned, the insufficient neutralization develops a positive electrical charge on a target, a substrate, leads to additional beam divergence and appearance of undesirable oscillations and instabilities of the main ion source' operational parameters, discharge voltage V_d and current I_d, and, as a consequence, makes a negative impact onthe ion beam energy E_i and current I_i. For those who work on specific thin film processes, it is recommended to calibrate an ion source measuring the electrical potential on the target for the operational conditions ($\dot{m}_a$, V_d, I_d, working gas type). [*Magnetic field is supposed to be constant in such measurements.] It is desirable that the electric potential measurements will be on a probe with area close to the utilized in

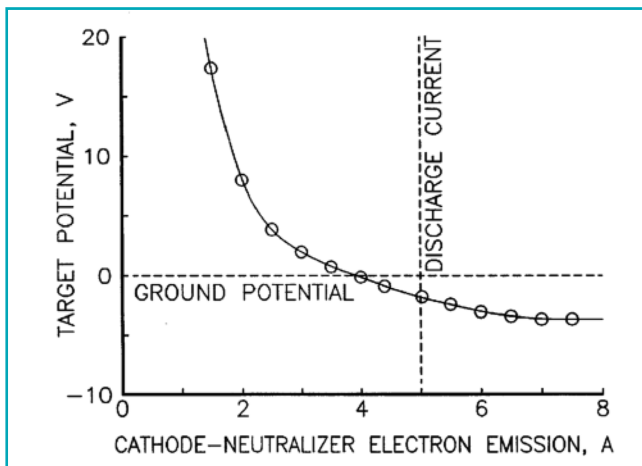

Figure 3. Electric potential applied to target at various emission currents I_{em} for discharge current $I_d = 5$ A [13].

practice and, certainly, a positive electric potential should be reduced to a zero value; and in this case, one can have the optimum emission current for any specific process.

It is important to note that an underneutralized ion beam even of few volts can produce neutralizing sparks that can be detrimental for fine thin film process [11]. However, an extra negative potential to a target caused by excess of electrons does not produce any noticeable sparks at moderate negative potentials of ≤ 15-20 V, because electrons due to their high mobility dissipate fast into a surrounding vacuum chamber.

Hall-current ion sources that have been utilized as broad beam ion sources for thin film technology [1-9] are mainly of two types: closed drift ion sources (CDIS) of the magnetic (MLIS) and anode layer (ALIS), and end-Hall type. All these ion sources operate very well when a cathode produces electrons that ionize working gas and neutralize developed ion beams.

However, there is a series of closed drift ion sources, especially, of the anode layer types that do not use external sources of electrons and operate in the regime of a self sustained discharge [1]. Such ion beams in order to maintain discharge must generate electrons neutralizing a space charge. In this case, electrons are generated during ions collisions with discharge channel walls and with targets, substrates and vacuum chamber walls.

The tendency of ion beam for the neutralization of its space charge can be estimated [14] through the electric field strength E_o on an ion beam surface with radius R and an ion beam length L, when a non-neutralized cylindrical shape beam in the result of self-expansion under impact of a space charge increases its radius, for example, in two times.

The electric field strength on an ion beam surface can be expressed as:

$$E_o = 2\pi R^2 en/R = 2I_i/(Rv), \qquad \textbf{(1.1)}$$

The beam's length at which the beam's radius is doubled can be determined as:

$$L = 2RN \approx 1.6v/\omega_{oi}, \quad \omega_{oi}^2 = 4\pi\varepsilon^2 n/M, \qquad \textbf{(1.2)}$$

where N is a number of beam's diameters in the length L, I_i is the ion beam current; M is an ion's mass; v is an ion's velocity; n is an ion current density.

For Argon, at the ion energy of 1 kV (typical discharge voltage for ALIS) and an ion beam current of 1 mA the beam's radius will be doubled for N ≈ 12. In such a case, on the beam's surface the electrical field strength will be $E_o \approx 290$ V/cm. The ion beams with the currents of about 1 mA expand fast and develop around itself a very strong electric field. At the same time, for the thin film tasks it is necessary to have the ion currents of several amperes, not milliamperes. As one can see, such ion beams can exist only in the neutralized state.

The ion beams up to tens of milliamperes can be obtained with the gridded ion sources. However, because in the gridded ion source's acceleration region the ions space charge is not neutralized by electrons, the maximum value of the ion beam current is limited; this limitation is expressed by the Child-Langmuir law of "two-thirds" determined by formula:

$$I_i = (4/9)(2e/M)^{1/2}V^{3/2}d^{-2}, \quad (1.3)$$

were e is electron charge, M is ion mass, V is potential applied between two plane electrodes. It is assumed a one-dimensional flow of single-charged ions. For the gridded ion sources the ion beam neutralization takes place outside an ion source. In some cases, gridded ion sources could provide an ion beam current up to 1 A. But that is achieved with the utilization of accelerating high-voltage potentials and large number of holes.

This consideration is very important for linear ALIS that operate without cathodes producing neutralizing electrons. The ALIS ion beam will be quite expanding and develop high positive potentials on targets and substrates, if certain measures for an ion beam neutralization are not undertaken. This important feature must be considered for every particular thin film task.

However, if the ion source system operates with the excessive neutralization, meaning that the neutralizer's electron emission current is higher than the ion beam current, there will be realized the opposite case of a negative charge build-up with the excess of electrons. And, since the electrons from usually utilized neutralizing devices have a relatively low energy of a few electron-volts, the excess of electrons of electrons leads to a few volts or less and, in general, does not produce such damage to a substrate as the excess of a positive charge; electrons disappear (to grounded vacuum chamber parts) fast due to their high velocity.

There are many different cathodes-neutralizers on the market and in the R&D state for ion sources and electric propulsion thrusters such as: Hollow Cathode Electron Source [15], Hot Filament Electron Source, Plasma Bridge Electron Source [16], RF Electron Source [17], Nonambipolar Electron Source [18], Microwave Discharge Neutralizer [19], and some others.

The majority of industrial ion sources are equipped with one of two types of electron sources: Hot Filament (HF) Electron Source (about 75-80% of all ion sources) and Hollow Cathode (HC) Electron Source (about 15-20% of all ion sources).

These two very different cathode devices are mainly analyzed in this article in some details. However, some other Electron Sources are described too.

2. HOT FILAMENT ELECTRON SOURCE AND THERMOELECTRON EMISSION

HF Electron Source for development and emission of electrons utilizes the thermoelectron emission (TEE), which is generation of electrons from a surface of heated electrically conducting materials. For the first time the phenomenon of thermoelectron emission was discovered by T.A.Edison [20].

Richardson-Dushman Formula for the Current Density of Thermoelectron Emission.

For the rectangular potential barrier Richardson and Dushman [21] calculated the maximum current density (saturation current) of thermoelectron emission that can be provided by a cathode at temperature T with a cathode's material work function φ:

$$j = A_o T^2 \exp(-\varphi/kT) \quad (2.1)$$

where $A_o = 4\pi mek^2/h^3 = 120.4$ A/cm²K² is the Richardson constant (in some references, it is called also as the Sommerfeld thermoemission constant); T is a cathode's temperature in K; φ is a cathode's work function; k is the Boltzmann constant, $k = 1.38 \cdot 10^{-23}$ J/K, h is the Planck constant $1.55 \cdot 10^{-34}$ J·s, m and e is mass $9.1 \cdot 10^{-34}$ g and charge $1.6 \cdot 10^{-19}$ C of electron.

The formula (2.1) was obtained in the assumption that an emitter's surface is uniform and an electron gas is in the state of thermodynamic equilibrium. In practice, these criteria very frequently do not perform. The value A_o for majority of pure metals is in the range from 15 to 350 A/cm²K². For the ion sources and thrusters, where Tungsten is quite frequently used, the Richardson thermoemission constant A_o, which is usually taken in the electron emission calculations, is equal to 120.4. In recent time this value was a subject of special studies by research groups working on Hollow Cathodes for space electric propulsion. For example, in [22] there are analyzed theoretical and experimental comparisons for the A_o values with the experimental measurements. In this work the theoretically calculated value for Tungsten at T = 2500 K of $A_o = 60$, and the experimentally measured in [23] is 40-60; for Tantalum the theoretical value for T = 2500 K is $A_o = 63$, and the experimentally measured [23] is 60.

Tungsten and Tantalum wires are usually utilized for a hot filament cathode electron source. Electric current applied through such a wire heats it up to high temperatures of 2500-2600 K and emits electrons according to formula (2.1). As one can see, the formula (2.1) shows very strong dependence of thermoelectron emission from temperature. For calculations the equation (2.1) is utilized usually in the following form:

$$j = 120.4T^2 \exp(-11600\varphi/kT), \quad (2.2)$$

where j is in A/cm², φ is in eV. The thermoelectron emission current is determined from expression: I = jS, where S is the area of emitting cathode surface.

Let us make some calculations for the Tungsten HF cathode (φ = 4.5 eV) that usually is made out of a thin wire in a form of a spiral that has area equal to about 10 cm² [*For a Tungsten wire with the length of 30-35 cm and the thickness of 0.5 mm, that is typical dimension of the HF utilized in practice with end-Hall ion sources of Mark-2, EH-1000 type; the wire's operating temperature is usually from 2300 to 2640 K]. From these data it is easy to calculate a HF emission power using formula (2.2) and the power of thermal radiation:

$$P_r = S\xi\sigma T^4, \quad (2.3)$$

where ξ is the effective integral coefficient of radiation (sometime called as emmissivity) of a heated Tungsten wire that in various literature sources is assumed from about 0.3 to 0.4; σ is the Stefan-Boltzmann constant that is equal to $\sigma = 5.67 \cdot 10^{-12}$ W/cm²K⁴. It is important to note that in the HF electron sources quite a large part of the heating power is produced by a thermal radiation.

The wire's heating power is a sum of a thermal radiation power and a power responsible for an electron emission, or

$$P_h = S\xi\sigma T^4 + jS/[e(\varphi + kT)] \quad (2.4)$$

Another important characteristic of a HF is its lifetime t_{lf}, which, if one would neglect the damage producing by an ion beam, is

determined by the evaporation rate of a HF material according to the formula:

$$t_{lf} \approx C_1 \exp(-q/kT), \quad (2.5)$$

where q is a cathode's evaporation heat, C_1 is a constant.

The HF cathode efficiency η is determined by the ratio of the current density saturation to the specific power of heating p_h that must be applied to the cathode for maintaining the stationary operation. Or it can be formulated as the electron current obtained per unit of a heating power P_h, or:

$$\eta = I/P_h = j/p_h. \quad (2.6)$$

After substituting the Richardson-Dushman formula in (2.1) and neglecting the η power dependence of T, one can obtain:

$$\eta \approx C_2 \exp(-\varphi/kT), \quad (2.7)$$

where C_2 is a constant.

With the increase of working temperature the thermocathode emission ability and efficiency increase according to the formula (2.2) exponentially. However, the lifetime decreases also exponentially according to the formula (2.5). Usually, the thermocathodes have efficiency from about 5 to about 100 mA/W, when they operate at low temperatures under 2000 K, and the lifetime can be up to several thousand hours in ideal conditions of a regular lamp. In reality, in operation with ion sources there are special factors, like high operation temperatures up to 2300-2500 K and higher and ion bombardment of a HF wire that reduce the HF lifetime drastically to just a few hours.

In majority of Hall-current ion sources, a hot filament is in form of spiral, **Figure 4a**. There are some companies that have their ion sources in a form of a straight wire [24], **Figure 4b.** In most cases, the spiral breaks at the center, on the ion source axis, because the ion beam current is usually is higher on the ion source axis, if it well focused. However, it can break in various places, if it not focused and poorly neutralized ion beam.

Another important consideration for the HF electron source is the uniformity of temperature distribution over the emitter-spiral surface. This is one of the most crucial conditions for stable and long life operation. First of all, the uniformity of temperature distribution depends on the selected method of heating and on a design of the electron source. Usually the HF is heated by a power supply with an alternating current. However, some ion source producers (Sainty [24]) utilize a direct current and a simple straight Tungsten wire (**Figure 4b**).

In **Figure 4c**. one can see an end-Hall ion source made by Russian company Luch [25] with a HF in a form of arc type straight Tungsten wire. However, in this work an ac power supply is utilized.

According to measurements [13], the lifetime of the HF spiral with ac current exceeds the spiral using a dc current supply by a factor of two. During the dc supply a non-symmetrical distribution of electrical potential over a HF spiral takes place, and at the ac the potential is distributed uniformly with the frequency of a power supply, from 50-60 Hz to over 25 kHz [26].

In **Figure 4d.** there is shown end-Hall ion source of Beijing Vacuum Matai-ke Technology Company that that has two Hot Filaments with purpose of increasing a HF lifetime during technological process, operating with one HF at the time. And when one HF will be burned, the other one will be turned on [34].

Figure 4a. Mark-2 end-Hall ion source with a Tungsten HF (in a form of spiral) electron source produced by Veeco Instruments.

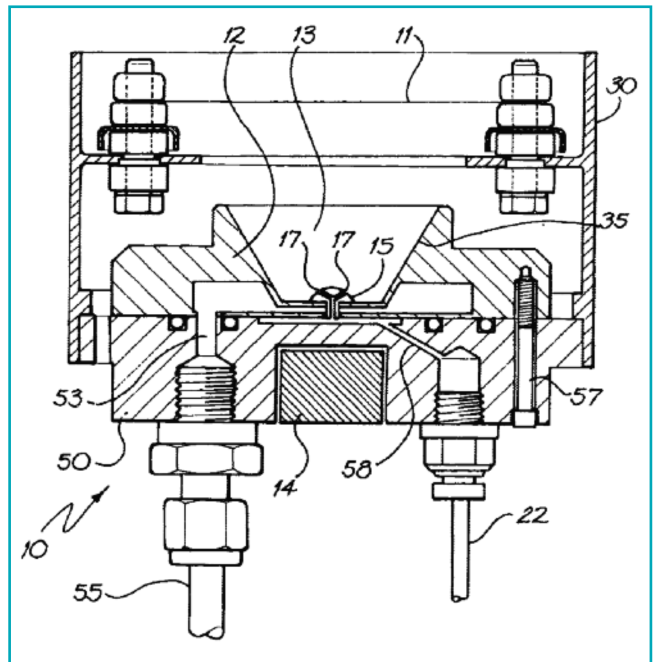

Figure 4b. Sainty's end-Hall ion sources with a straight Tungsten wire 11 as a HF electron source.

In **Figure 4e** there is shown a new approach to the HF electron source with the end-Hall ion source [12], when a HF is surrounded by screen with the purpose to reduce an ion beam contamination from a HF Tungsten particles and to reduce substantially the radiation effects on certain radiation sensitive targets-substrates. This type of arrangement of a HF should be

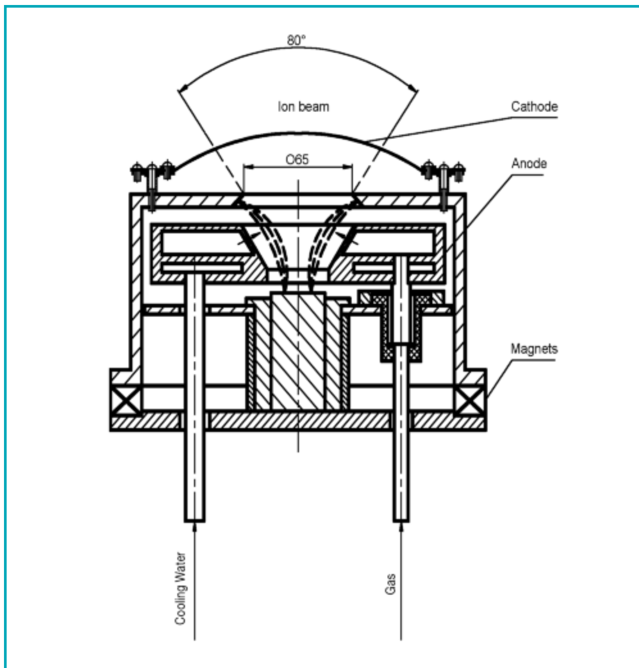

Figure 4c. End-Hall ion source of Russian company Luch with a arc-type HF.

Figure 4d. End-Hall ion source of Beijing Vacuum Matai-ke Technology Company with two Hot Filaments for a HF longer operation time.

properly "tuned" in the sense that a HF wire distance from an end-Hall's front flange and a screen should be tested for specific cases of discharge currents and voltages and working gases. This is not a simple HF arrangement, but can be very useful for some tasks.

It is necessary to calculate thoroughly a Hot Filament's length and its area for particular operational conditions of an ion source. Using the Richardson-Dushman formula one can estimate a preliminary value of the electron emission that can be provided by a HF with existing power supply.

Remembering that the heat released in a Hot Filament is expressed by a simple Joule formula $Q=RI^2t$, where Q is heat in Joules, R is a HF resistance in Ohms, I is current in Amperes, t is

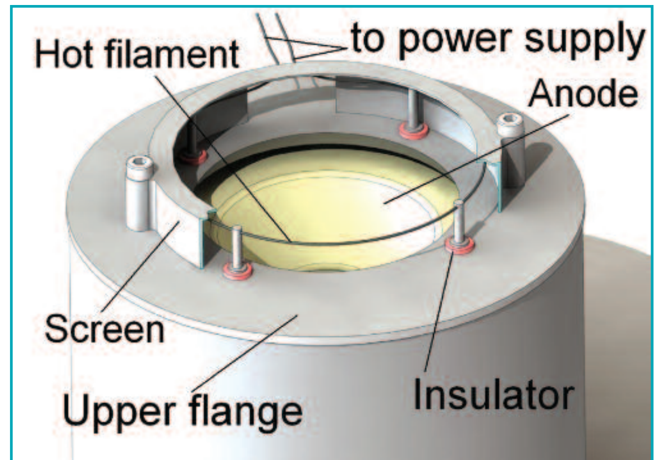

Figure 4e. Hot Filament cathode of ring form with screen to reduce ion beam contamination and radiation impact on target-substrate [12].

time in seconds. In this formula, however, R is changing with temperature according to the approximate formula $R = R_o + aT$, where R_o is the HF material's resistance at low (room) temperature; a in the first approximation is considered as a constant value, but at high temperatures this value changes drastically. With the alternating current utilization for a HF, the heat released in a HF will be expressed by the formula:

$$Q = (I_o \sin\omega t)^2 (R_o + aT)t \qquad \textbf{(2.8)}$$

The HF temperature change can be determined by the formula:

$$dT/dt = W/c_p - T/\tau_{th}, \qquad \textbf{(2.9)}$$

where W is electric power released and dissipated in a HF; c_p is a HF wire heat capacity at constant pressure; τ_{th} is the thermal time constant characterizing the wire physical properties, its form and surrounding environment. The solution of differential equation (2.9) takes several assumptions and approximations [27] and has the form:

$$T = T_o + T''\sin(2\omega t + Z), \qquad \textbf{(2.10)}$$

where Z is a phase constant. The voltage as function of time can be expressed as:

$$V = V'\sin(\omega t + C) + V''\cos(3\omega t + f), \qquad \textbf{(2.11)}$$

where C is the constant, f is the phase constant measured in experiments. The formula (2.11) shows that electric potential is distributed mostly uniformly over the HF length. But at the direct current application to the HF wire it has the potential's maximum at one end of the HF wire (usually it is a plus-anode [*do not get confused with an ion source' anode]) and minimum at the other end (usually it is a minus-cathode).

The uneven potential distribution leads to uneven distribution of temperature and makes a HF lifetime short in comparison with the alternative current. Experimental results with the end-Hall EH-1000 [13] for Argon with $I_d = 5$ A and $V_d = 150$ V gave for a dc power supply the HF lifetime equal to about 3.17 h and for an ac power supply (50 Hz) it was about 5 h.

As one can see, the comparison of operation of a HF wire with

a dc and ac power supplies gives significant advantage to an ac power. However, there are other factors that can seriously influence on a HF wire lifetime. One of these factors is a distance of a HF spiral from the ion source's front plate. [*Note: HF is usually is placed on the front plate's holders, and at the distance that can be changed is actually the distance from the discharge area which is a subject of transitions with an ion beam coming out from being influenced by electric and magnetic fields.] This HF distance can be regulated by movement of the cathode supports.

In earlier published information about a HF behavior in different working gases it was stated that reactive gases, such as Nitrogen and Oxygen reduce a HF lifetime. However, in recent works it was found that reactive gases actually increase a Tungsten HF lifetime due to development of a thin film like tungsten nitride WN [*Tungsten nitride forms together with tungsten dioxide, tungsten trioxide, and tungsten pentoxide while the filament is heated] and tungsten oxide compositions. Such thin films are happened to be developed at high temperatures and are more stable to an ion beam sputtering than just pure Tungsten.

The sort of working gas influences significantly on the HF lifetime, t_{lf}. As a rule for the same ion source's applied discharge power ($I_d = 5$ A, $V_d = 150$ V, or W = 750 W) for the working gas Argon $t_{lf} \approx 5$ h, for Oxygen $t_{lf} \approx 5.5$-6.0 h, and for Nitrogen $t_{lf} \approx 8$-10 h for end-Hall Mark-2 type ion source with the Tungsten for the wire diameter of $d_w = 0.5$ mm (0.020"); for $d_w = 0.64$ mm (0.025") the lifetime is higher by approximately as the rate of wire diameters, or about 1.3 (all numbers are for ac power supply). The lifetimes of a HF Tungsten spiral of 0.5 mm thickness with the discharge current of $I_d = 5$ A as a function of the discharge voltage V_d for various working gases, Ar, O_2 and N_2 for end-Hall Mark-2 type are given in **Figure 5.**

One of several factors influencing the HF lifetime is the quality of a Tungsten wire. For better results, it is necessary to select Tungsten wires of several makers for comparison, because, as it was noticed, Tungsten producers make various products of the wire that influences its operational lifetime; sometimes even different wire batches give different lifetimes.

Almost constant HF lifetime in the region of discharge voltages from about 250 V and up to about 600 V can be explained by the fact that the range of discharge voltages from about 350 V and up for discharge is the region of a self-sustained discharge. As it was discussed earlier [1-3] and shown in **Figure 6**, an ion beam becomes more divergent and its main parameters, discharge voltage and current, experience noticeable oscillations.

In **Figure 6** there are shown the typical Volt-Ampere Characteristics (VAC) of a Hall-current gridless ion source. As it was discussed in our previous publication in *VT&C* [1-9] the discharge from about 20-50 V and to about 300-370 V represents itself a form of so-called non-self-sustained discharge [*range of a non-self-sustained discharge voltages differs for different gases and even for different discharge currents; however, the tendencies are very similar] that in order to be maintained needs an external source of electrons for ionization of a working gas and for neutralization of ion beam. From about 20 V and to about 220 V a non-self-sustained discharge has a mode called as a distributed discharge. A non-self-sustained discharge in this mode also operates in the most efficient way, with a high transformation of a discharge current into an ion beam current, and with a low erosion rate of a discharge channel and other parts such as magnetic poles by an ion beam.

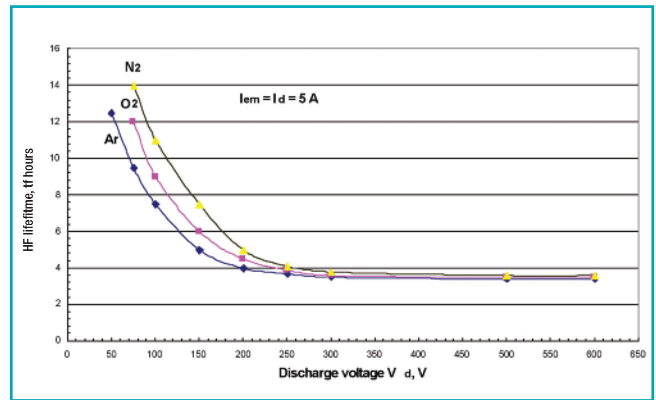

Figure 5 End-Hall ion source Tungsten HF lifetime as function of discharge voltage V_d for discharge current $I_d = I_{em}$ work working gases such as Ar, O_2, N_2; HF wire is 0.020" (0.5 mm) diameter; $I_{em} = I_d = 5$ A; ac Power Supply

Comparing the Tungsten wire life time curves of **Figure 5** with the Volt-Ampere Characteristic that is shown in **Figure 6** for a working gas Argon [*It is necessary to note that Volt-Ampere Characteristics for Oxygen and Nitrogen are very similar, except that the maximum ion beam current values for both gases are higher than for Argon by a factor of 1.2-1.3], one can see the following similarities. The HF lifetime is higher at low discharge voltages from about 50 V to about 100 V. And then gradually goes to the practically constant value of the lifetime of about 3.5 h at high discharge voltages for all tested working gases.

In case if one would assume that the HF evaporation due to a Joule heating is not the major factor in the HF lifetime, here are the other factors producing impact on the HF lifetime: **a**) the ion beam impingement on the HF wire leads to bigger damage at higher energies, **b**) the distributed discharge mode produces less damage at low energies, **c**) it is important whether ion beam is (relatively) focused or divergent.

In general, the analysis of processes leading to destruction of the HF electron sources showed that the following factors produce direct impact on a HF lifetime.

Conclusion about Hot Filament electron source

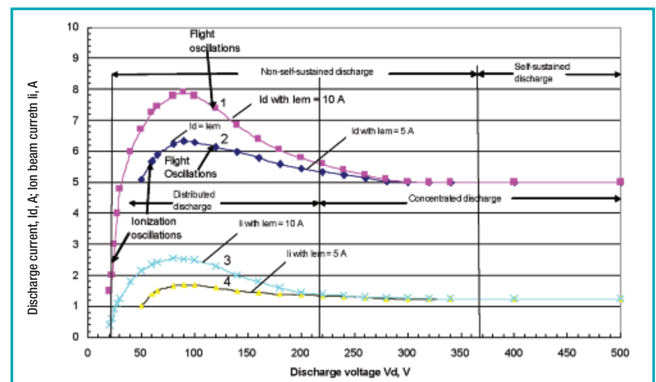

Figure 6. V-A Characteristics for Hall-current ion source with I_d and I_i as functions of V_d for $I_d = I_{em} = 5$ A, and $I_{em} = 10$ A; working gas Argon.

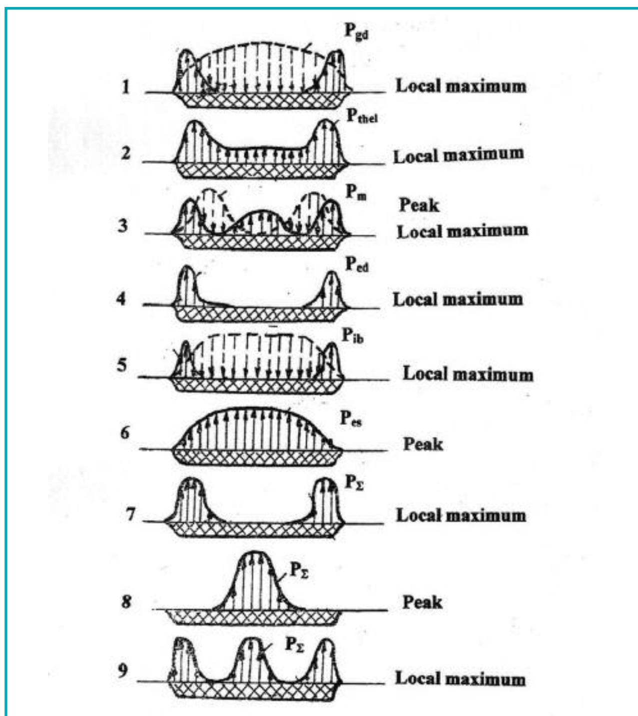

Figure 7. Possible variants of pressure distribution on cathode's surface in result of action of different mechanisms such as: 1 – gasdynamic, 2 – thermoelastic, 3 – magnetic, 4- electrodynamic, 5 –pressure of ion beam flow, 6 – electrostatic; 7, 8, 9 – possible variants of pressure distributions [32].

1. Change of geometry of a HF wire due to a thermal evaporation caused by ejection of metal in a liquid and solid phase, and sputtering by ion beam.
2. Impact of stationary and quasi-stationary temperature stresses changing thermo-physical and mechanical parameters leading to the wire destruction.
3. Fast application of current with sharp heating leading to development of the thermal shock and destruction due to the non-stationary temperature stresses.

It is necessary to note about the interconnection of above mentioned factors and complexity of development of a theoretical model for the HF lifetime calculation. Experimental measurements of the HF lifetime are very limited by some references [28] and manuals for the end-Hall ion sources [29, 30]. In theoretical works about the erosion of cathodes there are suggested various mechanisms of destruction, which are electrodynamic, ion beam flow, thermoelastic and combined an ion beam erosion with a thermostress [31, 32].

In **Figure 7** there are given several pictures of possible pressure distributions on the electrode caused by various impacts such as electrodynamic, ion beam flow, etc [32]. Pressure distributions are in relative units. The following designations for pressure are used in **Figure 7**: P_{gd} – gasdynamic, P_{thel} – thermoelastic, P_m – magnetic, P_{ed} – electrodynamic, P_{ib} – ion beam, P_{es} electrostatic, P_Σ - total.

As one can see, the situation with all various factors that affect on a heated wire is very complex and can be solved only by numerical calculations, and only with many unknown values. Those shown pressure distributions can produce substantial damage, and when the critical change of the electrode's geometry exceeds the admissible, or $P > P_{cr}$, a heated wire breaks. So, the practical approach is simply to provide experimental dependencies of a HF wire lifetime as function of specific working gas and its operational parameters: an ion beam current I_i and an ion beam mean energy E_i.

1. The HFs main advantages: they are cheap, and simple in utilization: easy to assemble-substitute; in certain thin film processes are quite reliable. Power supply is also simple and cheap.
2. The HFs disadvantages are: they are of comparatively low lifetime and can introduce undesirable contamination in to an ion beam. As it was above discussed, a HF evaporates during operation of the end-Hall ion source; for example at the ion source optimum parameters ($I_d \approx$ 5-7 A, $V_d \approx$ 100-150 V) and applied powers of about 700-1000 W the Tungsten HF erosion rate is about (2-3) $\cdot 10^{-5}$ g/s.
3. Another disadvantage is a comparatively high power applied to the HF by a power supply up to about 400-600 W, which is released in the form of radiation propagating in practically all directions and in the direction of an ion beam. Its power in some cases is comparable with an ion source and during works with the temperature-sensitive substrates such as polymers and certain fiber-optics materials the additional radiation from a HF leads to unnecessary heating besides the heating produced by an ion source itself. Unfortunately, there was not much research on optimum operation of HFs with ion sources; however, in [28] there are given good basic physical descriptions and hot filament properties for emissions in A/cm for various diameters of Tungsten and Tantalum wires.

The HF assembly shown in **Figure 4e** [12] one can see the method of reducing a HF excessive radiation on certain temperature-sensitive materials, and contamination produced by a HF material (Tungsten, Tantalum). HFs of various dimensions and forms, besides utilization with ion sources, have been used even with space EP devices. For example, one of Russian satellites was equipped with a magneto-plasma-dynamic thruster in the space experiment "Kust" [33a], and cathode was made of a Tungsten wire with the diameter of 1.5 mm. This quite unusually thick wire was supposed to sustain long duration operation. Also, there were conducted some separate investigations of possible substitutes for HFs of different materials (W, LaB_6, Hf) operating not only in inert gases (except Helium), but also in oxidant medium (air) [33b].

Hot Filament electron source does not utilizes working gas directly, but it must be immersed in plasma and to be in electrical coupling with plasma, because it can experience the space-charge limitations.

Acknowledgements

The author thanks Prof. A.I.Bugrova (Russian Institute of Radio-Electronics, Moscow), Prof. K.N.Kozubsky (Fakel Enterprise, Kaliningrad, Russia), Prof. M.Kristiansen (Texas Tech Uni-

versity, Lubbock), Dr. L.A.Goncharov ("Platar", Moscow, Russia) for collaboration in this work.

Special thanks to Dr. P. Tsygankov (Bauman Technical University, Moscow, Russia), Dr. E.V.Klyuev and Dr. A. Sidorov ("Luch", Podolsk, Russia) for helping with certain experimental work that was utilized in this article.

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