End-Hall Ion Sources with Reduced Heat to a Magnet

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ABSTRACT

Broad beam cylindrical end-Hall ion sources for the thin film technology are presented with the magnet isolated by a soft iron cylinder from a hot plasma discharge. Such arrangement permits utilizing various magnets with low and high magnetic field values making possible obtaining ion beams with low and high energy for specific thin film tasks. It is shown that such ion sources operate quite stable in various ranges of discharge voltages (energies) with noble and reactive gases. This iron piece serves for protection not only from high temperatures, but from an ion beam that has tendency to be accelerated not only into exit side of ion source, but also into a gas distributor (reflector) side. Certain improvements and future features in design and operation of ion sources are suggested.

INTRODUCTION

The Hall-current ion sources operation is based on the physical principles of electron magnetization, on increase of plasma resistance and electrons lifetime, during which electrons can interact with neutral particles and ionize them effectively. This concept was implemented for the development of modern electric propulsion devices for space apparatuses that have been transformed and used now as ion sources.

In the ion sources electrons are magnetized, if $\omega_e \tau >> 1$ (ω_e is electron cyclotron frequency in magnetic field; τ is average time between electron collisions with other particles and discharge channel walls). Ions usually are not magnetized, $\omega_i \tau << 1$, and move under applied electrical field between anode and cathode. During discharge in magnetic field electrons move to anode due to collisions with the working gas molecules, ions, discharge channel walls, and also due to oscillations. Ions are not influenced by magnetic field, move from places of origin, at or close to anode into a cathode direction along electric field. Flying from source an ion flow captures necessary number of electrons for neutralization and develops what is called an ion beam; though the ions are accompanied, in general, by electrons. Electrons drifting in the azimuth direction neutralize ions space charge in the discharge channel. In Hall-current ion sources, contrary to gridded ion sources, there is no limit for ion beam current that exists in gridded ion sources caused by a space charge of ions. It also means that gridless ion sources can produce high ion beam currents at low energies under 100 eV.

Part of regular operation of Hall-current ion sources is existence of varieties of oscillations of discharge current and voltage. Operating magnetic fields depends on ion source dimensions, but, as a rule, magnetic fields in a discharge channel are not very high: from about 100 G to maximum 500 G. However, some ion sources, so-called Anode Layer Ion Sources (ALIS), which do not have an external source of electrons, can operate at substantially higher magnetic fields up to several kG, especially when they operate in the self-sustained regime [1] at high discharge voltages up to 3 kV.

In end-Hall ion sources, the discharge channel has a cylindrical form with a massive hollow conical anode. Cathode serving as a source of electrons is usually in a form of a Hot Filament (HF) or a Hollow Cathode (HC). Electrons are magnetized, in general, only at the exit part where magnetic field has a radial component. The magnetic field in a discharge channel and in the whole magnetic circuit of an ion sources is provided by a permanent magnet (or, in some cases, a magnetic coil utilizing external power supply of a constant current) that usually is placed in area close to a gas distributing system and anode. In order to have sufficient magnetic field values in a discharge channel the magnetic poles of the magnetic circuit are designed being close to each other. At the ion source exit magnetic field is quite low, because end-Hall ion source utilizes the permanent magnet's magnetic field that sharply decreases from the place under anode where a gas distributing system is located. Usually a magnetic field value on the permanent magnet top is about 1-1.5 kG, and at ion source exit this magnetic field is reduced to about 50-75G. Due to this fact, the end-Hall ion source is considered as the source with a negative gradient of magnetic field.

End-Hall ion source is one of the most extensively utilized in thin film technology for sputtering, etching (recent method with high discharge currents and high discharge voltages), ion assisted deposition, magnetron with ion assisted deposition, electron beam with ion assisted deposition, biased target deposition.

VAC TEC END-HALL ION SOURCES

VAC TEC Company developed two varieties of end-Hall type ion sources: VTC-2 (front flange diameter for ion beam exit is 45 mm) and VTC-5 (front flange diameter for ion beam exit is 76 mm) [1]. VTC-2 has a range of discharge voltages from

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about 50V to about 200V for most known in thin film technology working gases (Ar, O_2, N_2, etc). VTC-5 has a range of discharge voltages from about 80-100V to about 300V. These ion sources have a piece of soft iron on the top of magnets as a part and continuation of an ion source's magnetic circuit. The utilized Alnico magnets have the Curie temperature of about 720°C. SmCo magnets have a maximum service temperature of about 250-300°C (depending on chemical composition); Alnico magnets have maximum service temperature from 520 to 550°C. But SmCo magnets can deliver higher magnetic fields: over 3000-5000G, if necessary. And they are cheaper than Alnico-8, which is one of the most "popular" magnets now. End-Hall ion source schematic drawing VTC-2 is shown in Figure 1.

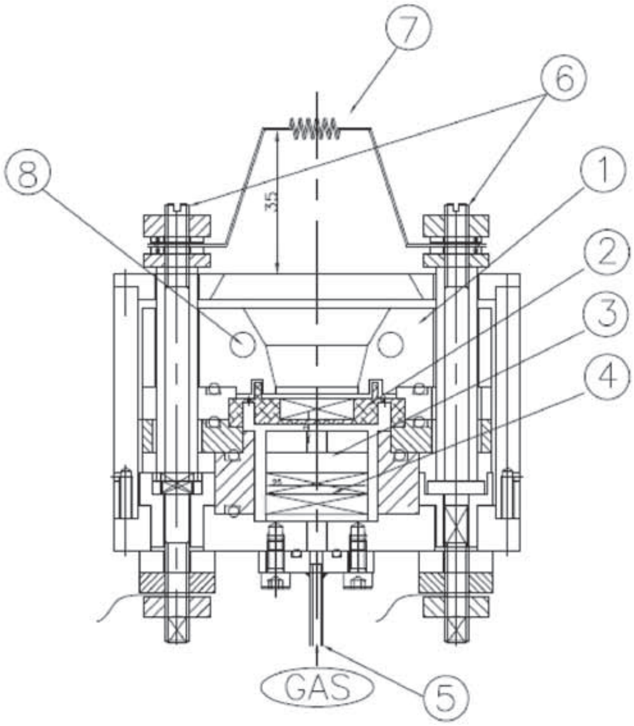

Figure 1: VTC-2 [1] end-Hall main parts: 1 – anode; 2 – reflector; 3 – soft iron between reflector and magnets for reducing heat flow to magnets; 4 – magnets; 5 – working gas; 6 – electrodes for Hot Filament Cathode, 7 – Hot Filament (it distance from front exit flange can be regulated for optimum HF lifetime); 8 – water cooling

The utilization of magnets with broad range of magnetic fields in some cases is proved to be very practical. In this work there are several layers of SmCo magnets that can be put together as one strong magnet or with just one magnet separated by pieces of soft iron in a magnetic circuit. It means that magnetic field in the area of the end-Hall discharge channel can be changed from low of about 300-500G on the top of a gas-distributing system (reflector) to about 2000-3000G. In one of our previous publications [2] it is shown that end-Hall ion sources the maximum achieved discharge voltage is proportional to the applied into discharge channel magnetic field. In general, higher the magnetic field, higher the maximum discharge voltage obtained in end-Hall ion source, and it follows approximately as $V_{d,max} \sim B^{1/2}$.

In recent years there are observed several tendencies in thin film technologies such as:

1. Utilization of gridless ion sources and, in particular, end-Hall ion sources instead of gridded complex design high energy ion sources.
2. High ion beam currents from 1 to 2A. The ion beam current I_i in gridless end-Hall type ion sources, in general, is about 0.2-0.3 of the discharge current I_d, or $I_i \approx (0.2\text{-}0.3)\cdot I_d$. In other words, for obtaining ion beam currents of 1-2 A it is necessary to have discharge currents of 5-10A.
3. Low mean ion beam energies from about 20 eV to about 50 eV. The ion beam mean energy E_i in gridless ion sources is about 0.6-0.7 of the discharge voltage V_d, or $E_i \approx (0.6\text{-}0.7)\cdot eV_d$. It means that for $E_i \approx$ 20-50 eV it is necessary to have $V_d \approx$ 30-80 V. Such energies are good for the ion assisted processes and for the biased target deposition, when ion beam energy must be lower than the threshold sputtering energy for most known in thin film technology materials.
4. High mean ion beam energies from about 300 eV to about 500 eV. In order to substitute the high energy gridded ion sources it is necessary to have the gridless ion sources that can operate at discharge voltages of about 500-800V. Because a mean ion beam energy in the gridless ion sources is $(0.6\text{-}0.7)\cdot V_d$, one should have the mean ion energies of about 300-500 eV, which are optimum for the sputtering-etching tasks.

END-HALL THERMAL REGIME AND MAGNETIC FIELD DISTRIBUTION

End–Hall ion sources, as any device experiencing electrical discharge with applied power $W = I_d \cdot V_d$, has certain thermal regime that is determined by its geometrical factors and the cooling means. Because end-Hall ion source has a magnet, or a series of magnets placed under a discharge channel, it delivers magnetic field that decreases approximately as $1/l^2$ from a magnet's top. It also means that such ion source has a negative gradient of magnetic field in a discharge channel.

Negative gradient of magnetic field with mainly magnetic field lines in the axial direction, as it was discussed in one of our works [2], leads to the situation that an ion beam is accelerated not only into the exit part, but also into the opposite side, into the gas-distributor reflector. In result, the reflector becomes substantially eroded by an ion beam and heated. The heat from the reflector and other parts of the discharge channel and anode during ion source operation gradually spreads around the whole ion source's body, heats the other parts of ion source such as flanges, gas distributing system, magnet, or magnets, etc.

Most parts of the ion source can sustain high heat flux, however, magnet, or magnets are quite susceptible to high temperatures and, when their temperature achieve and exceeds the Curie temperature* an ion source loses necessary magnetic field for proper operation. Some consequences include a problem of operation at high range of discharge voltages and development of strong voltage and current oscillations with transitions into arcs.

In vacuum, when a mean free path for particles is substantially longer than any characteristic dimensions, electromagnetic radiation is main mechanism of a heat transfer. It means that magnet or magnets must be placed at substantial distance from a source of high temperature; they have to be insulated from such high temperatures.

Analysis of temperature distribution shows (Figure 2 top) that the temperature on the magnet's top is acceptable for practically all high applied powers; for regularly utilized in practice discharge parameters of $V_d \approx 125$-150 V and $I_d = 5$ A. The maximum temperature for such a case is about 200°C. This temperature distribution is for the radiation cooled anode. It is necessary to note that the complete time for establishing temperatures shown in Figure 2 (top) is about 150 min and 80% of the maximum values takes about 120 min.

The magnetic field distribution (Figure 2) shows the values at the reflector of about 1000G and at the ion source exit flange about 300G. This particular case is good for high discharge voltages up to 300V and higher.

At least, their temperature must not exceed the Curie temperature of utilized magnets in the ion source. In some cases, if a high working gas flow is applied through magnets, it can increase a heat transfer between the reflector and the magnet through a convective heat process. Also, it can cause a pulsed heat transfer during a sharp vacuum chamber opening. In such a case, it is necessary to give some time for the whole system with ion source for cooling.

This is one of the reasons why many end-Hall ion sources producers make ion sources with water-cooled anode. VTC ion sources also have water-cooled anodes and they are successfully cooled at quite high applied powers of about 1.5 kW and higher.

The magnetic field distribution for the end-Hall type ion source was calculated numerically with the soft iron piece placed on top of the magnet. Soft iron piece continues the magnetic path close to the discharge channel and helps to have still high values of magnetic field even it is placed quite far from the second magnetic pole (external flange).

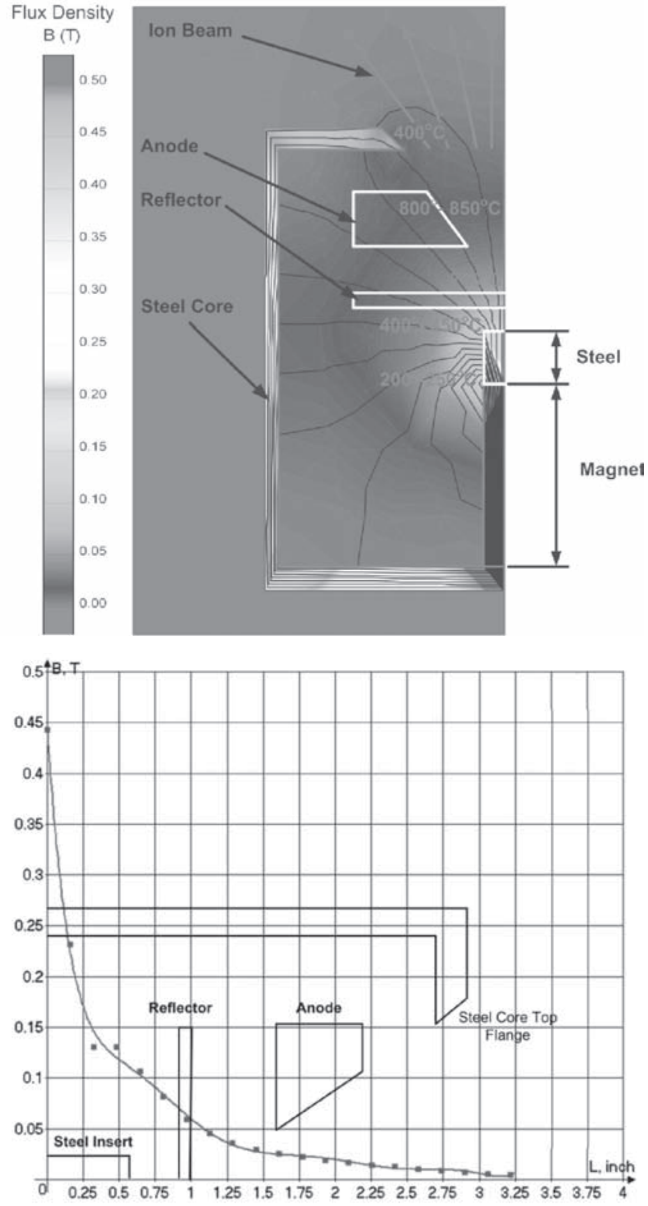

Figure 2: Magnetic field and temperature distributions in end-Hall ion source with soft iron steel placed on top of magnet at applied power of 750-1000 W.

**The Curie temperature of a ferromagnetic material is the temperature above which it becomes paramagnetic and loses magnetism.*

The distribution of temperatures in the end-Hall discharge channel and the magnetic system was estimated and in some points was measured. The temperatures are shown for sufficiently high applied electric powers between about 750 and 1000W that are extreme for these ion sources. Because these estimations and measurements were for the radiation cooled anode, it means that the thermal regime for a water-cooled anode will be substantially milder, and one can expect that the temperatures at magnet will be reduced by about 75-100°C.

EXPERIMENTAL RESULTS

In Figure 3 there are presented experimental results of VTC-2 end-Hall ion source for the Volt-mass flow $V_d = f(m_a)$ characteristics for discharge currents $I_d = 1, 2, 3, 5$ A; working gas oxygen. As one can see, the range of operating discharge characteristics are approximately from 80V to maximum 200V (Power Supply limit).

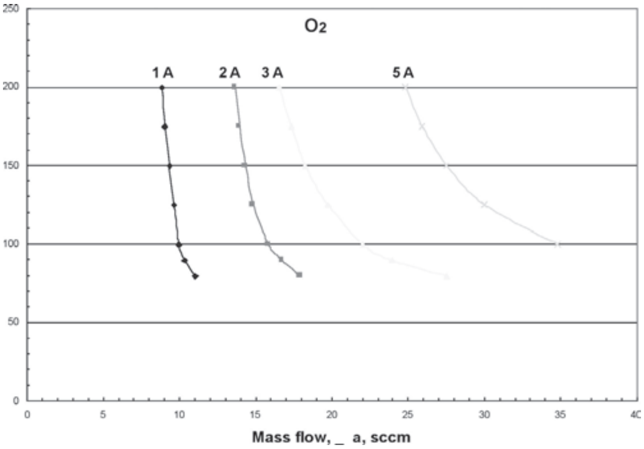

Figure 3: VTC-2 end-Hall; experimental Volt-mass flow $V_d = f(m_a)$ characteristics for constant discharge currents $I_d = 1, 2, 3, 5$ A; working gas oxygen.

In Figure 4 there are presented experimental results of VTC-2 end-Hall ion source for the Volt-mass flow $V_d = f(m_a)$ characteristics for discharge currents $I_d = 1, 2, 3, 5$ A; working gas argon. The range of operating discharge characteristics with argon is approximately from 50V to maximum 200V. It means that this ion source is a very good for an ion assisted and a biased target deposition tasks.

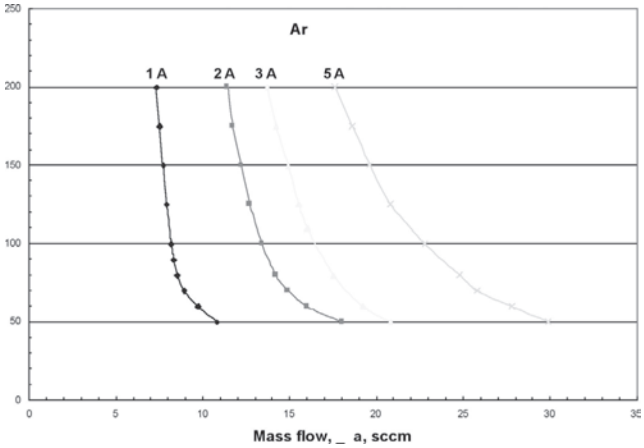

Figure 4. VTC-2 end-Hall; experimental Volt-mass flow $V_d = f(m_a)$ characteristics for discharge currents $I_d = 1, 2, 3, 5$ A; working gas argon.

In Figure 5 there are presented experimental results of VTC-5 end-Hall ion source for the Volt-mass flow $V_d = f(m_a)$ characteristics for discharge currents $I_d = 1, 2, 3, 5$A; working gas argon. The range of operating discharge characteristics with argon is approximately from 80V to maximum 300 V. This ion source has higher magnetic field at the reflector and can operate with the discharge voltage up to 300V. It is assumed, with different Power Supply and proper filter between a Power Supply and anode, it will be possible to have this ion source operation substantially over 300V, in other words, it can be used for etching and sputtering tasks.

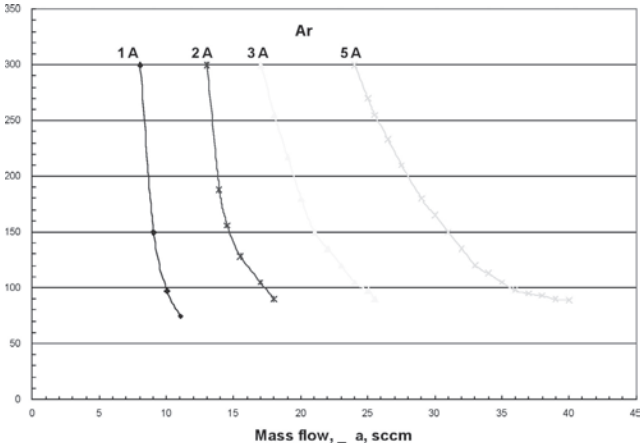

Figure 5. VTC-5 end-Hall; experimental Volt-mass flow $V_d = f(m_a)$ characteristics for discharge currents $I_d = 1, 2, 3, 5$ A; working gas argon.

As one can see, with VTC-5 it was possible to have discharge voltages at 300V for all discharge currents. In order to obtain lower discharge voltages it is necessary to utilize magnets with lower magnetic field of about 800-1000G, that can be done without problems.

DISCUSSIONS

The magnetic simulations specially made for VTC end-Hall ion sources indicate that the soft iron piece serves as a barrier for high radiation fluxes to the magnet and continues the magnetic path in the discharge channel. The temperature distributions are acceptable for thin film technology and magnets are going to be in operating conditions for quite a long time.

For VTC-5 the Volt-mass flow $V_d = f(m_a)$ characteristics for discharge currents $I_d = 1, 2, 3, 5$ A look smooth and even at quite high discharge current Id = 5 A it consumes very moderate mass flows from about 26 sccm to 40 sccm. VTC-2 for the same currents, due to smaller dimensions has lower mass flows. It also means that these ion sources would not need very high power vacuum pumps.

As one can see, the ion sources operate in stable condition and do not experience any oscillations and instabilities [3] from low to high discharge voltages and currents. It shows that magnetic field of permanent magnets is selected correctly.

The VTC end-Halls have flexible magnetic field configuration with a series of permanent magnets, easily substituted (reduced-increased number of magnets) that can be used to reduce, or increase magnetic field; and that leads to a smooth discharge parameters change in various environments from noble gases to reactive gases such as oxygen and nitrogen. These end-Hall ion sources are quite stable with existing contamination from dielectric and insulating coatings. They are very well suited for industrial applications.

About VTC end-Halls ion beam currents and mean energy.

Both ion sources VTC-2 and VTC-5 generate the ion beam current that are about 0.2-0.25 of the discharge current, or $I_i \approx (0.2\text{-}0.25)\cdot I_d$. At the same time, the ion beam mean energies are about 0.6 of the discharge voltage, or $Ei \approx 0.6\cdot Vd$ (in eV).

With argon as a working gas a VTC-2 end-Hall ion source in general operates with the discharge currents range $I_d = 1.0$A to 5.0A and that corresponds to the ion beam currents of $I_i \approx$ 200-250 mA and up to $I_i \approx 1.0\text{-}1.25$A; the discharge voltage range is from $V_d = 50\text{-}200$V and that corresponds to the mean ion beam energies of $E_i \approx (30\text{-}120)$ eV. VTC-5 end-Hall can, in principle operate from $I_d = 1.0$A and over 5A with discharge voltages under 100V and over 300V with the mean ion beam energies from about 50 eV and about 200 eV.

The analysis and experimental results show:

- The end-Hall ion sources utilizing a soft iron piece in front of a permanent magnet provides protection to a permanent magnet from excessive high temperatures that can be applied to the ion sources.
- The optimum selection of a soft iron piece in front of a permanent magnet can provide also various necessary magnetic field values into the ion source discharge channel closing a magnetic circuit for stable operation without significant oscillations of discharge voltages and currents.
- The optimum selection of the magnetic field in a discharge channel (under 1000G on reflector) can provide low discharge voltages (low energies) for ion assist, biased target deposition and other tasks in thin film deposition.
- The optimum selection of the magnetic field in a discharge channel (over 1000G on reflector) can provide high discharge voltages (high energies) for sputtering and etching.
- VTC-2 and VTC-5 End-Hall ion sources can provide broad range of ion beam mean energies from low energies of about 30 eV to high energies of about 200 eV and ion beam currents over 1 A. These ion sources are capable to have ion beam energies up to 300-500 eV with noble and reactive gases and ion beam currents over 2-3A and experiments with high discharge voltages are under way. This range of energies and currents covers practically any modern thin film deposition technologies: ion assist, sputtering and etching processes.

ACKNOWLEDGEMENT

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