Gas discharge electron sources – Proven and novel tools for thin-film technologies

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Gas discharge-based electron sources represent high-power and low-cost tools for a variety of processes regularly required in vacuum high-rate coating. Here, the fields of substrate pre-treatment, electron beam generation for materials evaporation, plasma activation in PVD, and post-treatment steps are of particular concern. In this paper, some of Fraunhofer FEP's recently refined as well as novel tools shall be reviewed. These include low-voltage electron beam sources utilizing hollow-cathode arc discharges, high-voltage glow-discharge axial EB guns with a new hybrid cathode, and a short-pulsed high-intensity electron source which has evolved from channel-spark devices and features ablative vaporization of the target material. For sampling, development of new technologies and pre-production qualification of hardware key components, a cluster tool comprising all these electron sources has been commissioned recently.

Газоразрядни източници на електрони – доказани и нови инструменти за тънкослойни технологии (Г. Матауш, Б. Цимерман, Ф. Фиетзке, Й. Хейнц, Б. Граффел, Ф. Винклер, Ф. Роегнер, Х. Метцнер). *Използващите газов разряд източници на електрони представляват мощни и евтини инструменти за различни процеси, редовно необходими при вакуумното високо-скоростно напластяване на слоеве. Тук, областите на предварителна обработка на подложката, генерирането на електронен сноп за изпарение на материала, плазменото активиране при физическото парно отлагане, следващата обработка са от особен интерес. В тази работа са разгледани, някои от скоро подобрените, както и нови инструменти във Фраунхоферовия институт по електроннолъчеви и плазмени технологии в Дрезден. Обзорът съдържа ниско-волтови източници на електронни снопове, използващи дъгови разряди в кух катод, аксиални електронни пушки с високо-волтови тлеещи разряди, с един нов хибриден катод, и един късо-импулсен електронен източник с висок интензитет, който е развитие на канално-искрово устройство и използва аблативното изпарение на материала на мишената. За изпитване и развитие на нови технологии и пред-производствена квалификация на ключовите хардуерни устройства, беше скоро окомплектован един клъстерен инструмент, включващ всички тези електронни източници.*

Introduction and outline

The refinement of semi-finished products with decorative or functional layers is an important area of work in surface technology. Physical vapor deposition (PVD) processes in vacuum are versatile and environmentally-friendly. Economic characteristics, however, finally decide whether a desired technology can make its way into industrial mass production. High area throughput is one approach to save costs. Therefore, high-productive substrate pre-treatment, PVD coating, and post-treatment methods are required. In this regard, electron beam (EB) technologies are very promising. Equipment investment and running costs, of course, matter as well and need to be addressed, too.

This paper shall give an overview of various types of electron sources which are in use at FEP for different steps along the process chains in thin-film technology. The common link between the seemingly different tools selected for this review is revealed by the fact that the generation of free electrons is facilitated by gas discharges in all cases. The interested reader will certainly meet mature “work horses” of electron beam and plasma technology here but also some new, up-and-coming sources which are still in the development or qualification phase.

Versatile and compact low-voltage electron beam (LVEB) sources based on hollow-cathode arc discharges have proven their value in diverse applications but mostly as tools for plasma activation in high-rate PVD during the past years. By combining the hollow cathode source with pulsed power supplies, ignition of the discharge could be simplified and novel source designs became feasible recently.

The latest generation of high-power hollow cathode arc sources excels by magnetic enhancement which allows for creating plasmas with high and smoothly distributed ion densities in large volumes. They are tuneable within wide parameter ranges via the magnetic field strength and the working gas flow rate and can be adapted to various applications.

When used in plasma cleaning of metal sheets and strips, high etching rates have been measured - also with ferromagnetic substrates for which so-far established magnetron concepts usually fail. This opens the window to highly efficient and fast inline pre-treatment prior to coating.

Furthermore, new high-rate deposition methods as, e.g., the hollow-cathode arc-PECVD process could be developed and characterized utilizing a magnetically enhanced large-volume plasma source.

High-voltage glow-discharge EB sources with cold cathodes have previously been reported to provide an economically attractive alternative to conventional thermionic electron beam guns used in PVD. In this paper, a new type of discharge-based EB source with “hybrid cathode” will be discussed. It combines the simplicity of known cold cathode devices with beneficial performance parameters reached so far with traditional thermionic electron sources only.

Finally, a less-commonly known electron beam gun based on a modified channel-spark discharge device shall be introduced. This high-power / short-pulsed source features ablative vaporization of the target material thus preserving its composition and maintaining stoichiometry of the deposited layer. Further, this process is inherently tied-in with a high degree of ionization and energy of the generated vapor particles. Both effects promote the deposition of morphologically dense and well adhering thin films.

For development and pre-production qualification of novel technologies and enabling hardware key components, a cluster tool has been commissioned at FEP recently. The choice of instrumentation was determined by the desired main research focus of the new equipment, namely investigations in electron beam techniques and applications.

LVEB sources based on hollow cathode arc discharges as tools for plasma-activated PVD

For nearly two decades, hollow-cathode arc sources have been serving as universal tools for plasma activation in high-rate PVD to combine high growth rate with outstanding quality of the film by tailoring the energy of condensing particles and elevating reactivity when depositing compounds [1].

The hollow cathode arc discharge consists of two plasma regions: the internal and the external plasma (Fig.1). Within the hollow cathode tube, a dense plasma column (internal plasma) based on the flowing working gas provides ions, which are accelerated in the plasma sheath onto the cathode wall; the latter is heated to high temperatures by the ion bombardment. As a consequence, electrons are thermionically emitted by the cathode and accelerated by the cathode sheath potential into the plasma sustaining the discharge. A fraction of these electrons with energies of some tens of eV reaches the cathode orifice and drifts into the vacuum chamber. By a suitable arrangement of anodes (“annular anodes” integrated into the source or “booster anodes” placed in the vicinity of the evaporator), these electrons can be further accelerated and form a low-voltage electron beam (LVEB) which generates the technologically usable external plasma by collisions with the gas or vapor particles in the process chamber (Fig.2).

By combining the plasma source with bipolar pulsed power supplies, novel source arrangements became feasible such as the “Tandem Hollow Cathode” configuration (Fig.3). Here, instead of implementing external anodes for post-acceleration of the LVEB, two or more sources comprising a hollow cathode tube and an attached anode are used as discharge electrodes. The direction of the discharge is determined by the momentary polarity of the driving MF voltage pulses between opposite sources. Since no electrical isolation between a cathode and adjacent anode is needed, the design of the source compounds can be hold comparably simple and compact, whereas the acceleration of electrons across the process chamber ensures high ionization efficiency also under low-vacuum conditions as met, e.g., in “Directed Vapor Deposition” technology (Fig.4).

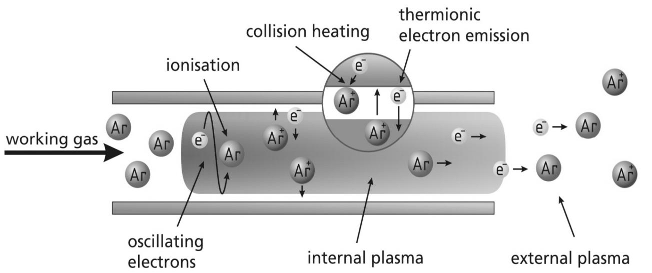


Fig.1.
Mechanisms contributing to the hollow cathode effect.

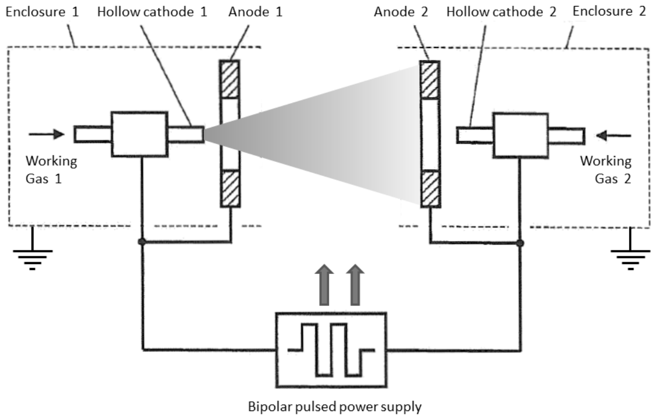
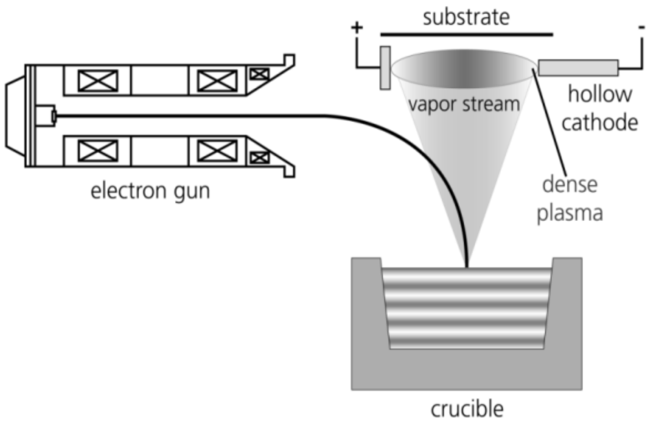


Fig.3.
Tandem hollow cathode (THC) arrangement powered by a bipolar pulsed MF supply. The arc discharge reverses its direction in sync with the time-dependent pulse polarity [2].



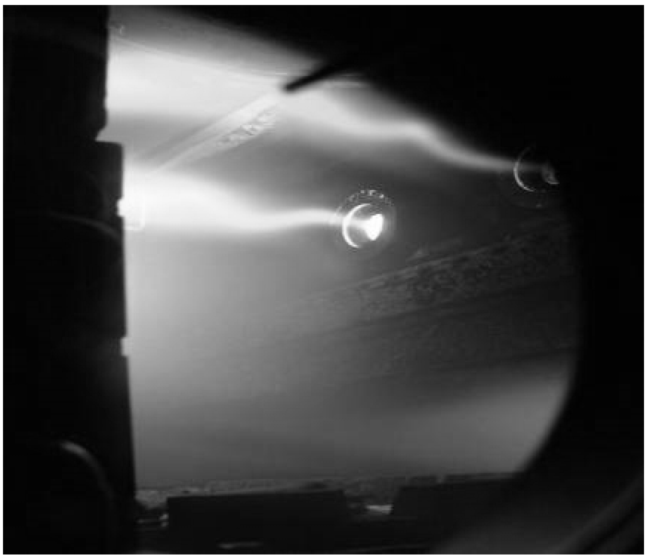
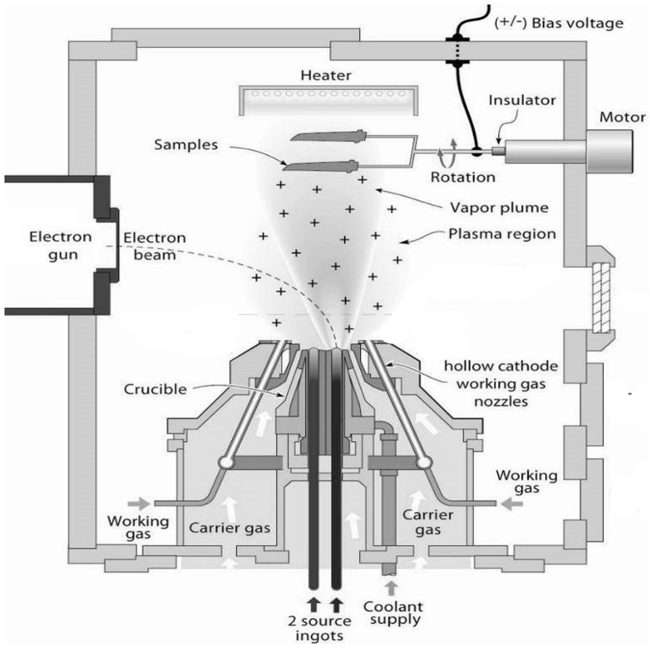


Fig.2.
Plasma-activation for high-rate EB-PVD of metal or compound films onto plastic webs by two hollow cathode arc sources, combined with external "booster anodes" (mounted opposite to the cathodes, not visible in the process image). The spiraling of the LVEBs is caused by a horizontal "magnetic trap" field which keeps secondary and backscattered electrons – which start at the evaporator upon impact of the high-power electron beam – away from the thermally sensitive substrate.



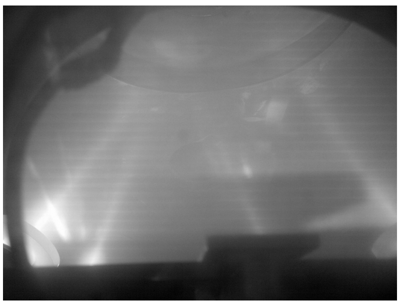


Fig.4.
Plasma-activation for "Directed Vapor Deposition" (a special EB-PVD method developed at the University of Virginia for gas-flow assisted coating of shaped parts) by a coaxial "Multi-Jet Hollow-Cathode" [3].
The four individual hollow cathodes were mounted under an angle to direct the LVEBs towards the coating zone thus increasing the plasma density nearby the substrate [2].

Large-volume plasma source based on hollow cathode arc discharge in an axial magnetic field

Plasma activation by means of hollow cathode arc discharges has been successfully applied in vacuum coating of plastic films and metal strips. Besides the main advantages such as the high plasma density and considerable self-bias potential as well as the comparatively simple, robust and cost-efficient structure of the plasma source and power supply, there are also a number of shortcomings which have hindered more widespread use of this technology. Noteworthy in this regard are in particular the locally concentrated inhomogeneous plasma, suboptimal ionization efficiency due to the low average energy of the emitted electrons and the high argon gas throughput of 100 ... 200 sccm required with traditional source designs (such as those in Fig.2) for stable operation, which makes the vacuum equipment of the coating plant considerably more expensive, and particularly so for systems having several sources as required in large-area coating. In order to overcome these disadvantages, the constructional design of a conventional hollow cathode plasma source was changed to allow a solenoid coil to be inserted into the annular anode surrounding the cathode tube [4].

The solenoid coil generates a toroidal magnetic field within the source and around the source (Fig.5). This field has two main effects. First, the anode is magnetically shielded, namely the path of the electrons from the cathode to the anode is made more difficult and the anode fall becomes more pronounced. Second, the hot cathode tube which emits the electrons is positioned in the center of the coil such that the magnetic field lines inside are essentially parallel to the cathode axis. In this way, the characteristic pendulum motion of the electrons inside the cathode tube which underlies the hollow cathode effect (Fig.1) is converted into a spiral motion around the magnetic field lines. This causes a lengthening of the electron trajectories and hence increased collisional ionization of the working gas forming the internal plasma. Thus, the magnetic field allows for reduction of the working gas flow rate through the hollow cathode tube resulting in a strongly enhanced cathode fall voltage drop and higher discharge power. Consequently, the plasma density, dissociation rates, or charge carrier energies in the external plasma can be significantly increased due to the higher kinetic energy of the electrons emitted by the hollow cathode.

The success of this measure can be seen from the ionization effect that is achieved in the space in front of the plasma source (Fig.5) and from the electrical characteristics of the discharge (Fig.6).

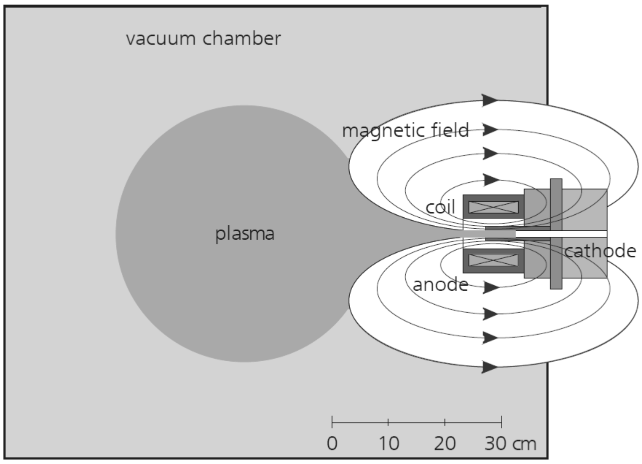


Fig.5.
Configuration and working principle of the magnetic field enhanced hollow cathode plasma source.

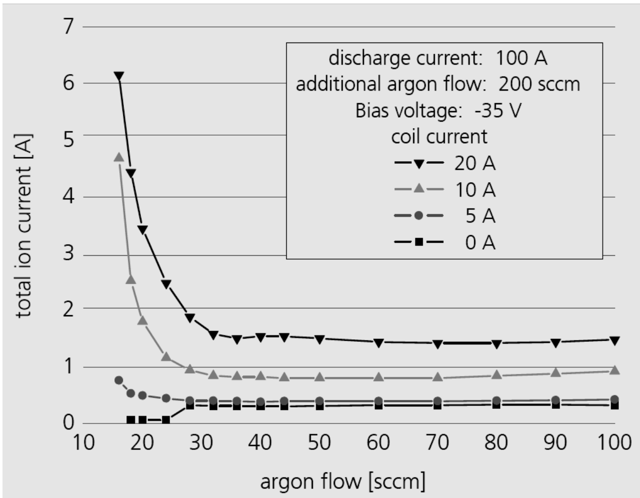


Fig.6.
With increasing magnetic field strength and decreasing gas flow the ion current extractable from the magnetic field enhanced hollow cathode plasma increases dramatically and reaches values which are more than an order of magnitude greater than those in "classic" operations without a magnetic field in the vicinity of the cathode.

discharge parameters:
- current 50-200 A
- voltage 40-150 V
- Ar flow 5-100 sccm
- axial magnetic field 0-100 mT
- ignition by voltage pulses of 800-1400 V within seconds

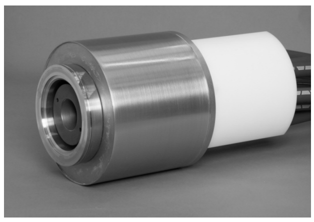


Fig.7.
Large-volume plasma source LAVOPLAS featuring magnetic field enhanced hollow cathode arc discharge.

Spatially-resolved measurement of the ion current density gave values of several mA/cm^2, even at distances of more than 500 mm from the source exit and far outside the cathode axis [5].

The new plasma source has already demonstrated its effectiveness in long-term stable operation over several hours at more than 20 kW. Using the power supply developed for this, there is also immediate and reliable ignition of the arc discharge by high-voltage impulses at the push of a button, without the need for a laborious procedure to heat the cathode tube up to operating temperature by auxiliary heater coils. The first trial applications indicated there is much potential for the new hollow cathode plasma source. Two examples, namely the pretreatment of metal strips and a PECVD process, both utilizing hollow cathode arc plasmas, shall be introduced in the following.

Surface pretreatment in metal strip coating by sputter etching using hollow cathode arc discharge

When developing coating processes, the prior substrate pretreatment step is highly important. It very often determines the adhesion strength and hence also the quality of the deposited layers. In metal strip coating, a special magnetron configuration wherein the discharge burns directly at the surface to be cleaned is commonly used for efficient inline pre-treatment today. This principle, however, cannot be used for thick ferromagnetic strips. Therefore, FEP developed the idea of positioning a positively biased hollow-cathode arc-discharge source in front of the substrate to be coated - which, advantageously, may remain at ground potential - and to use this dense plasma for sputter-etching [6].

Fig.8 displays an image of the process. A schematic of the setup and electric circuitry is shown in Fig.9. Typical discharge parameters are U = 25 ... 70 V and I = 200 A. The bias voltage was chosen to 500 V. An argon flow of 20 ... 100 sccm is required for stable operation. In order to suppress undesired micro-arcs, a MF pulsed bias voltage supply was used.

The dependency of the (static) etching rate on applied discharge power is displayed in Fig.10. At the highest tested power levels, a (gravimetric) material removal of 15 nm off steel sheets travelling at a speed of 100 mm/s was found. Different materials gave different etching rates due to the specific sputter yields of the argon ions (Fig.11).

As hollow cathodes are point-like plasma sources, the etching effect is naturally inhomogeneous. For that reason, several hollow cathodes must be arranged as an array adapted to the strip width [7].

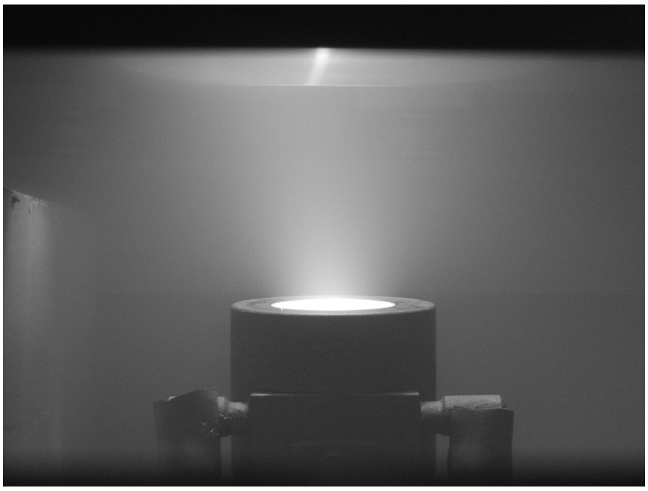


Fig.8.
Hollow cathode arc discharge during the sputter etching of a horizontally moving metal strip.

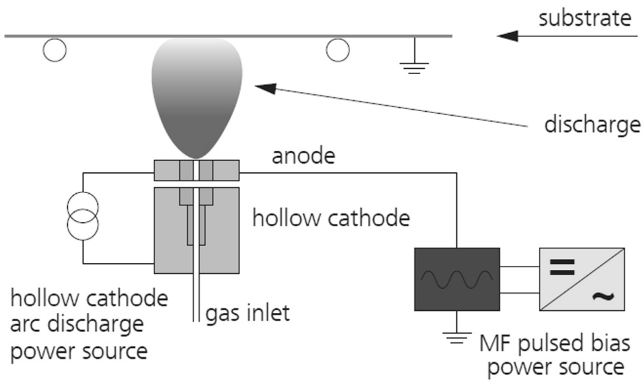


Fig.9.
Electrical arrangement of the hollow cathode arc discharge power source and of the MF pulsed bias power source for the sputter etching of grounded substrates.

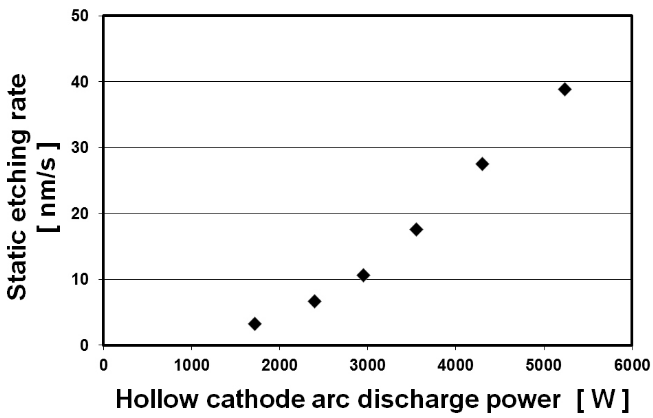


Fig.10.
Static etching rate of copper in dependence on the applied hollow cathode arc discharge power (working gas: Ar).

Introducing magnetic enhancement, there are also new perspectives on this. On the one side, the increased ion flow densities allow higher etching rates to be realized. At the same time, the directional characteristics are much broader, so that the number of hollow cathodes that have to be used across the strip width can be reduced. Further work on sputter-etching assisted by hollow cathodes will focus on further increasing the etching rate and the development of a cost-effective industrial usable unit.

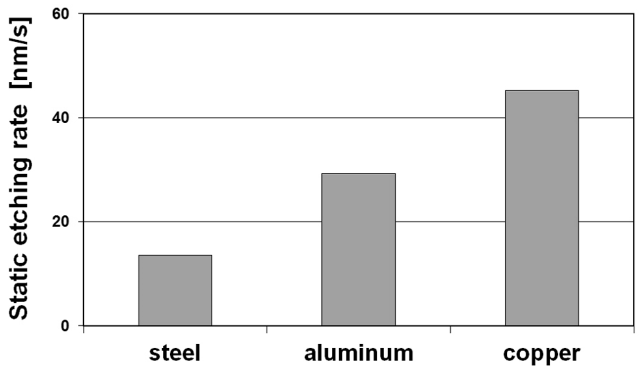


Fig.11. Static etching rates achieved for different materials.

High-rate deposition of amorphous hydrogenated carbon films by hollow cathode arc PECVD

Amorphous carbon films exhibit a wide range of properties and are of high importance in various application fields. Dependent on deposition conditions, soft polymer-like, hard diamond-like or graphitic film properties can be obtained. Mostly, diamond-like carbon (DLC) layers are favored for tribological coatings in order to reduce friction and wear of components. Further applications of a-C:H coatings are biocompatible coatings on implants or transparent polymer-like anti-reflective layers.

A variety of techniques is being utilized for the deposition of carbon-based films: Radio frequency-powered plasma-enhanced chemical vapor deposition (RF-PECVD) processes are widely used due to their technological simplicity and represent the standard technology in the DLC deposition industry; however, they suffer from a low deposition rate and limited layer properties as, e.g., film hardness (typically in the range of 20 GPa). Similar limitations hold true for magnetron sputtering of carbon. Higher deposition rates have been achieved by thermal arc plasmas and arc evaporation techniques, which either succeeded only on a laboratory scale or exhibited a highly complex technological assembly.

Recently, a hollow-cathode arc-based PECVD process (“arcPECVD”) has been developed for deposition with very high rates on components or large flat areas. The experimental setup is shown in Fig.12: In front of the hollow cathode arc device, an annular gas shower injected the acetylene gas into the dense plasma flame in the vicinity of the cathode orifice. The acetylene flow rates were between 200 … 1000 sccm. Below the gas shower, a sputter magnetron source was placed, which was equipped with a titanium target and operated in unipolar pulsing mode with a power of 2 kW. At a distance of 42 cm from the plasma source, a water-cooled substrate holder was mounted to which a d.c. bias voltage of up to 200 V could be applied. The bias voltage was negative with respect to ground potential, thus attracting positively charged ions from the plasma onto the substrates. The substrates were mounted on the hollow cathode's axis face to face with its orifice, and their temperatures were measured by a thermocouple. Different substrate materials have been coated by arcPECVD with a-C:H layers: stainless steel, glass, and n-doped silicon wafers. The latter were used for film characterization (Fig.13).

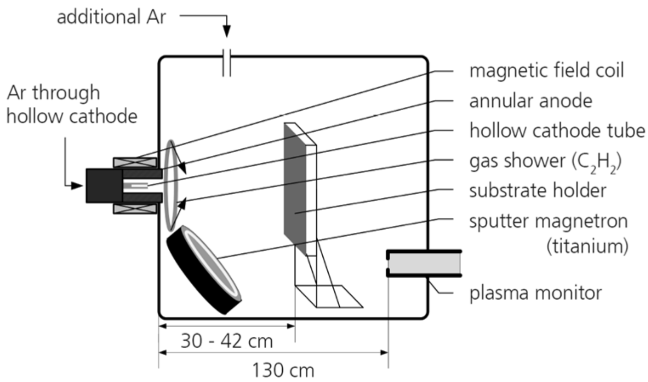


Fig.12. Experimental setup of the arcPECVD process.

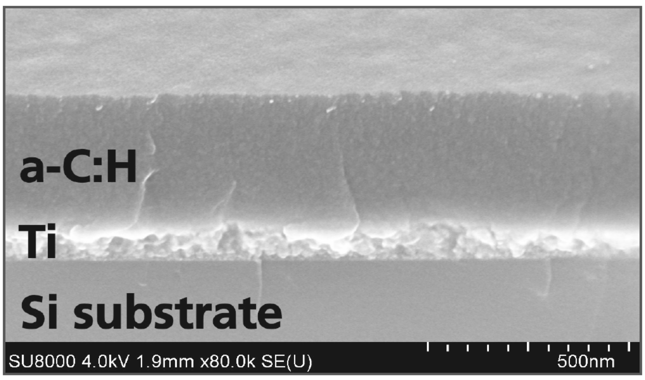


Fig.13.
SEM picture of a 250 nm thick a-C:H layer deposited by arcPECVD with a Ti interlayer on a silicon substrate.

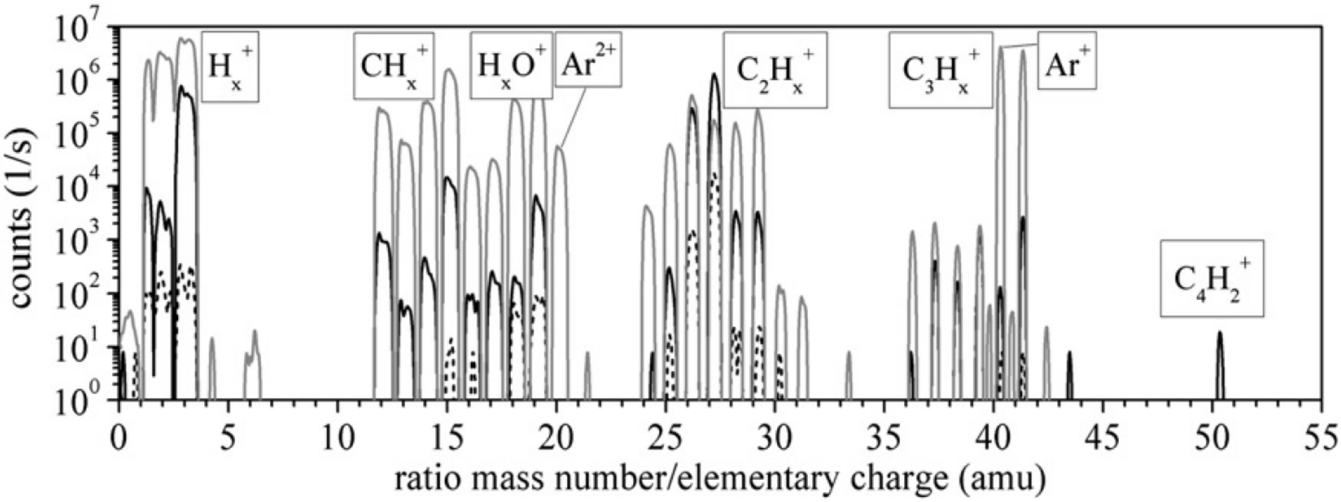


Fig.14.
Mass spectra of the acetylene arcPECVD plasma for different working gas flow rates (argon) through the hollow cathode tube (constant total argon flow rate into the chamber 100 sccm, acetylene flow rate 200 sccm, chamber pressure 0.3 Pa). The working gas flow rates are 100 sccm (black dashed line), 30 sccm (black continuous line), and 10 sccm (gray continuous line), respectively. The plasma power and hence the dissociation and ionization of acetylene is strongly increased by lowering the working gas flow rate through the hollow cathode tube. Not only dissociation, but also polymerization products with up to four carbon atoms could be observed.

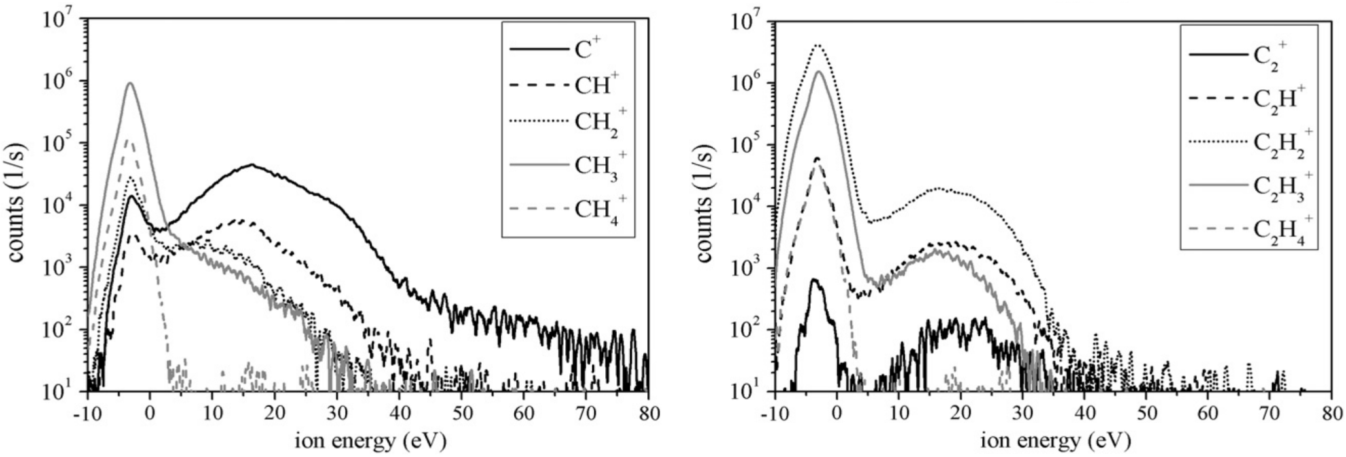


Fig.15.
Ion energy spectra of dissociation and polymerization products in the hollow cathode arc PECVD plasma (argon gas flow rate through the hollow cathode tube 15 sccm, acetylene 200 sccm, chamber pressure 0.1 Pa). The cathode and anode potentials are −20 V and 80 V, respectively, with respect to ground potential. The apparent negative energies arise from an internal offset of the analyzer. The spectra consist of low-energy peaks of ions from the bulk plasma as well as of high-energy tails of ions generated in regions of elevated plasma potential by the LVEB close to the hollow cathode orifice.

After hollow cathode-based plasma pretreatment of the substrates, a 100 … 200 nm sputtered titanium layer was deposited on the substrates in order to enhance the a-C:H layer adhesion. Subsequently, the hollow cathode arcPECVD step was carried out with a deposition time of 1 min to create the a-C:H layer (Fig.13). Whereas the working gas flow rate through the hollow cathode was kept constant at 15 sccm, the gas flow rates of acetylene and additional argon as well as the substrate bias voltage were varied. Energy-resolved mass spectrometry showed efficient dissociation of the acetylene molecules and subsequent polymerization. Reduction of the argon flow rate through the hollow cathode tube followed by increased energy of the electrons from the cathode strongly enhanced the acetylene dissociation (Fig.14). Moreover, the ion energy distributions revealed high energy tails of species (Fig.15).

By variation of the acetylene flow rate and of the substrate holder position, the deposition rate could be varied between 100 … 1000 nm/min; these high rates could be the key to industrial application of this process. Furthermore, the film properties could be controlled by the substrate bias voltage and substrate cooling between soft polymeric, graphitic, or hard diamond-like with a maximum hardness of 18.2 GPa (Fig.16). In comparison with typical RF-PECVD values, similar film hardness could be obtained at considerably higher deposition rate by arcPECVD [8].

film character	thickness (nm)	hardness (GPa)	H content (at.-%)	sp^3 content (%)
polymeric	250	7.8	42	40
diamond-like	250	18.2	31	25
graphitic	500	6.1	18	20

Fig.16.
Properties of a-C:H films deposited by hollow cathode arc PECVD under different process conditions [8].

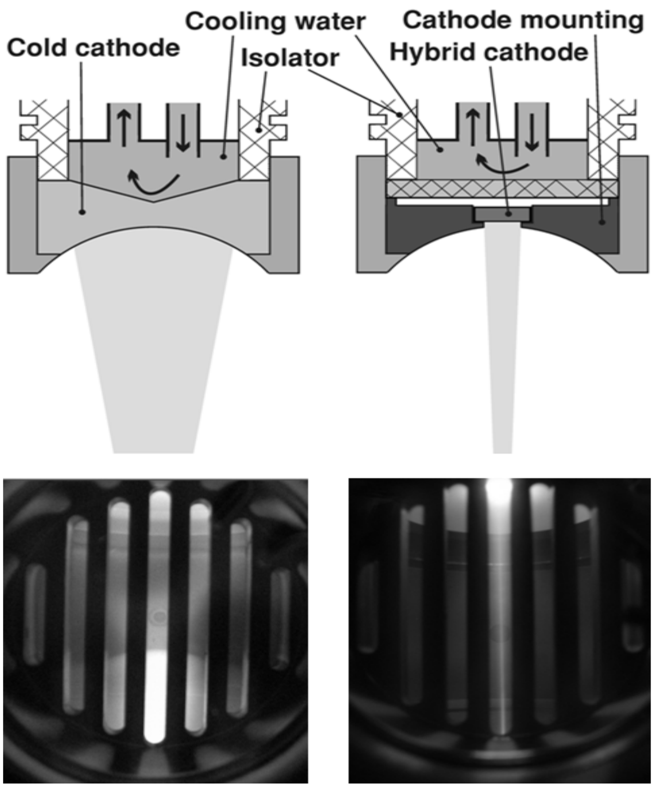


Fig.17.
Top: Schematic picture of a cold cathode (left) and of a hybrid cathode (right); Bottom: HVGD plasmas and generated electron beams with both cathode types.

High-power EB guns with hybrid cathodes

Electron beam sources provide the highest coating rates for industrial-scale processes and simultaneously produce deposited layers of excellent uniformity and purity. They can also be used with reactive, ferromagnetic and high-melting point layer materials. The majority of electron beam sources currently established in industrial processes employ heated refractory metal cathodes, viz. thermionic emitters. This principle causes a certain sophistication of the source design and complexity of the vacuum as well as electrical supply system. To overcome this drawback, cost efficient electron sources with cold cathodes and greatly simplified control and supply schematic have been developed [9].

Inside the cathode compartment of these electron guns, a high-voltage glow-discharge (HVGD) is sustained. Ions from the plasma are accelerated in the cathode fall and hit the cathode thus releasing secondary electrons which are accelerated across the plasma sheaths and then form the beam (Fig.17, left).

Whereas thermionic emitters require a high vacuum of better than 10^{-3} Pa in the cathode compartment, the operating pressure of the cold-cathode is in the range from 2 … 5 Pa. Differential evacuation of the beam source can hence be omitted up to a pressure of 1 Pa in the coating compartment, without relinquishing the main advantages of axial EB guns – technological universality, high power density, spatial and vacuum-wise separation of evaporator and beam source, and the related gain in reliability of the beam generation. The high voltage power supply requires no additional heating current source, usually floating at high potential. Contrary to the refractory metals to be used for the thermionic cathode and its supports, shielding, etc., suitable cold cathodes can be easily manufactured of aluminum at favorable cost and quickly changed without complicated adjustments having to be undertaken.

The cathode fall dimension accommodates itself to a change in the acceleration voltage and maintains the electrical field strength suitable for electron extraction from the cathode. Hence, no mechanical means for adapting the anode-cathode distance – as typically used with thermionic high-power EB guns for variable perveance operation – are needed.

The thus improved economic viability of cold-cathode EB systems may provide that also markets and applications which are currently rather being served by competing heating sources as, e.g., plasma torches (in vacuum metallurgy), lasers (in fusion welding) or boat evaporators (in PVD) come, cost-wise, into the reach of EB technology now.

Beside to these advantages, however, HVGD EB guns with cold cathodes exhibit also certain drawbacks which limit their use in PVD so far:

The beam generation efficiency η (expressed as the ratio between discharge current and electron beam current) of a HVGD EB gun is mainly determined by the secondary electron yield γ (emitted electrons per incident ion) of the cathode. Whereas pure metals show γ of less than or about 1, a dielectric film covering the cathode surface can increase this number up to an order of 10 (which corresponds to $\eta \approx 90\%$). The dielectric film has to be maintained during operation by admixture of a reactive gas such as oxygen to the plasma work gas. Naturally, operating an aluminum cathode in a glow discharge involving oxygen unavoidably leads to material removal by sputtering in the center of the cathode and redeposition of oxide in outer areas. Insolating deposits at the cathode, however, promote high-voltage breakdowns, likely triggered by surface charge flashovers. Therefore, the arcing rate of cold cathode HVGD EB guns and the related risk of imperfections in the deposited layers are significantly higher than with thermionic sources. Furthermore, the technically achievable stationary current density of secondary electron emission is of the order of 0.1 A/cm² only. EB sources with high nominal current rating have to utilize cathodes with considerable diameter therefore. Since the cross section of beams generated by these large-area cathodes is high, the power density at the work site can only by moderate - as dictated by electron-optical laws.

To keep the described advantages of cold-cathode HVGD EB guns but to avoid their shortfalls, a new plasma-based EB source utilizing a "hybrid cathode" has been developed at FEP (Fig.17, right):

The hybrid cathode consists of the electron emitting material surrounded by a part that serves as mounting unit for the emissive part and acts moreover as a field forming electrode. To generate the EB, a HVGD is ignited adjacent to the cathode which operates in the abnormal glow discharge regime. Therefore, the current can be controlled at constant voltage by regulating the gas pressure. To this point, the cold cathode and the hybrid cathode discharges are equivalent. The distinctive features of the hybrid cathode result from thermal isolation of and materials chosen for the central part. Due to the impinging ions, this part of the cathode is heated up until it predominantly emits thermionic electrons.

Regarding suitable material: lanthanum hexaboride (LaB_6) has proven to be capable of emitting secondary electrons when used in a glow discharge as well as thermionic electrons even at (compared to values needed for refractory metal cathodes) low temperatures. Admixture of reactive gases is not necessary for the hybrid discharge which runs best and at a markedly reduced arcing rate using pure and light plasma-forming gases such as H_2 and He. Only about a quarter of the working gas consumption of cold cathode guns is required with hybrid cathodes due to the specific discharge characteristic (Fig.18).

In the thermionic mode, LaB_6 can maintain emission current densities of the order of several A/cm². A hybrid cathode can hence generate a focal spot with reduced diameter and increased beam power density resulting in elevated materials evaporation rate and, not to forget, the opportunity to construct handier beam sources (Fig.19).

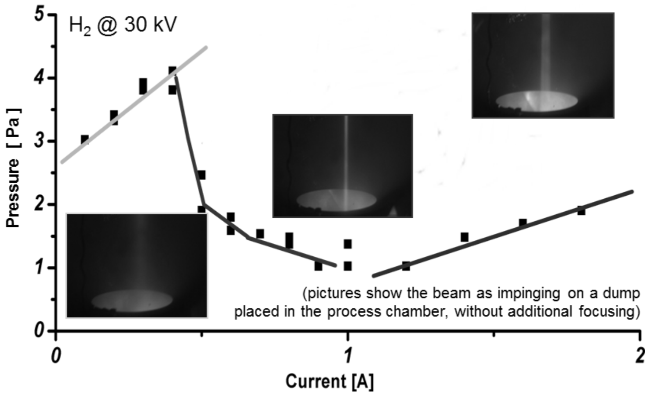


Fig.18.
Discharge characteristic (pressure in cathode compartment which represents a measure for the HVGD working gas flow vs. discharge current which is mostly carried by the run-away beam electrons) of a hybrid cathode EB gun operated at 30 kV acceleration voltage and with H_2 as working gas. Three different regimes could be observed and have been analyzed and modelled elsewhere [10].

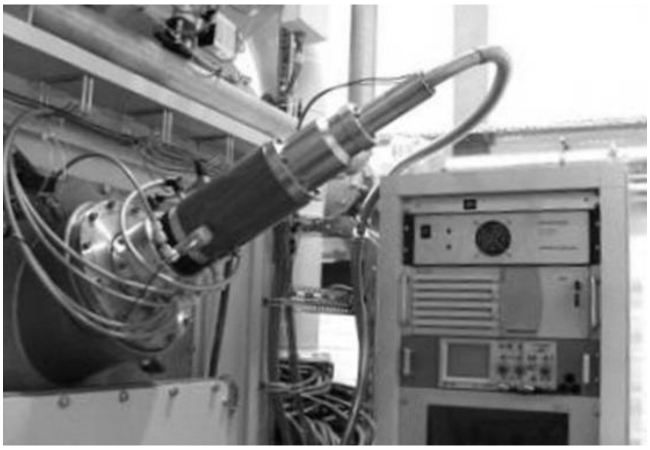


Fig.19.
Compact hybrid cathode EB gun rated 30 kV / 60 kW installed at an FEP pilot web coater.

Pulsed electron beam deposition

With the Pulsed Electron Beam Deposition (PED) process, a new field of work is evolving at FEP. This was enabled by a special EB source recently developed and delivered by *Organic Spintronics srl*. Its function principle relies on a channel-spark discharge. The source generates a short-pulsed, poly-energetic electron beam with a very high power density (≥ 10^8 W/cm² over a few nanoseconds). When directed to a target, the surface of the material is locally heated to an extent that ablation occurs, with subsequent propagation of the vapor towards the substrate in a directional flow [11].

As opposed to classic EB-PVD, the source material to be evaporated remains solid in PED. The advantage is that this allows for homogeneously depositing alloys in the proper stoichiometric ratio, because there is no accumulation of the less-volatile components due to the avoidance of a molten bath. Furthermore, the coating rate can be precisely adjusted facilitated by defined energy pulses.

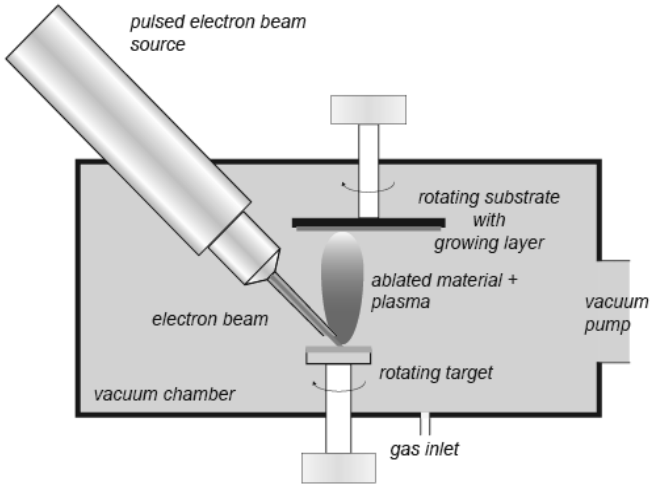
When compared to alternative Pulsed Laser Deposition (PLD), PED excels by lower system costs. An essential feature of the PED process includes its high variability: nearly all materials (both electrically conductive and insulating materials) may be ablated, and the energy utilization efficiency is high. The undesired deposition of micro-particles ("droplets") during layer formation can be markedly suppressed by optimizing the process parameters.

Beneficial particularities of PED include the formation of dense discharge plasma. It increases the energy of the ablated particles to several 10 eV and thus to a higher energy level than reached during electron beam evaporation or sputtering, for example. This positively influences the properties of the growing layers so that the substrate temperature can be kept low. Therefore, the growing of well-adhering, dense layers is also made possible on temperature-sensitive substrate materials – such as plastics, for example.

Moreover, reactive process control is possible by adding the corresponding gases. As a result, there are numerous different application possibilities such as the production of hard material layers, decorative layers, or transparent, conductive oxide layers. Further potential applications can be found in the field of flexible displays and in the domain of hetero-structured thermoelectric materials.

The first tests of the new source at FEP were intended to develop a general understanding of the PED process, as well as to investigate the suitability of the method for different applications.

For instance, the deposition of thin metal and semi-conductor layers was examined in process chains for photovoltaic applications. Furthermore, promising trials regarding the deposition of transparent conductive oxide layers were conducted.



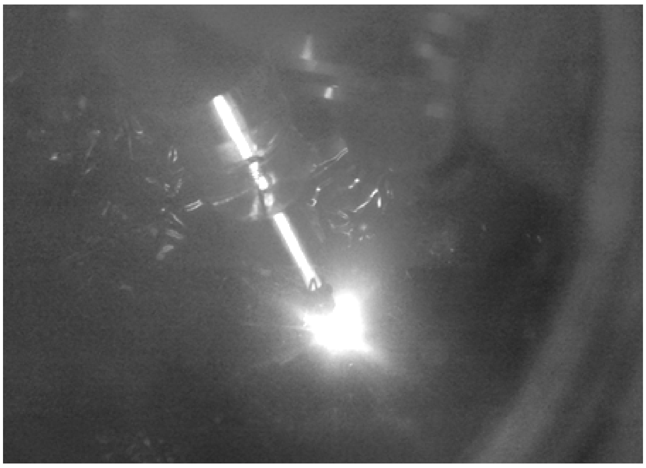


Fig.20.
Setup of the pulsed electron beam deposition process and PED source in operation.

Acceleration voltage:	up to 20 kV
Chamber pressure:	10^{-5} … 10^{-2} mbar
Extracted energy per pulse:	~1 J
Repetition rate:	0 … 100 Hz
Power density:	~10^8 W·cm^{-2}
Act. power density on substrate at 100 Hz:	~10^{-2} W·cm^{-2}
Typical layer thickness per pulse:	0.001 … 1 nm
Static deposition rate:	0.1 … 100 nm·s^{-1}

Fig.21.
Characteristic data of PED source and process [12].

ERICA cluster tool

FEP’s ERICA cluster tool comprises a load-lock and five separate process stations, arranged around a central chamber with a robot handler. This machine type allows the substrate to be transported in a continuous vacuum into the various process compartments in any desired sequence. Thus, complex production lines including pre-treatment, coating and thin-film processing steps can be simulated in a highly flexible way and at favorable cost. Regarding the implemented tools, special emphasize was put on various types of electron sources. For instance, the instrumentation of one chamber allows execution of high-rate EB-PVD processes. It comprises a hollow-cathode arc-plasma LVEB source (featuring, likewise, pre-treatment by sputter etching or plasma-activated deposition) and a hybrid cathode EB gun for materials evaporation. In another chamber, the PED source and target manipulation system is installed.

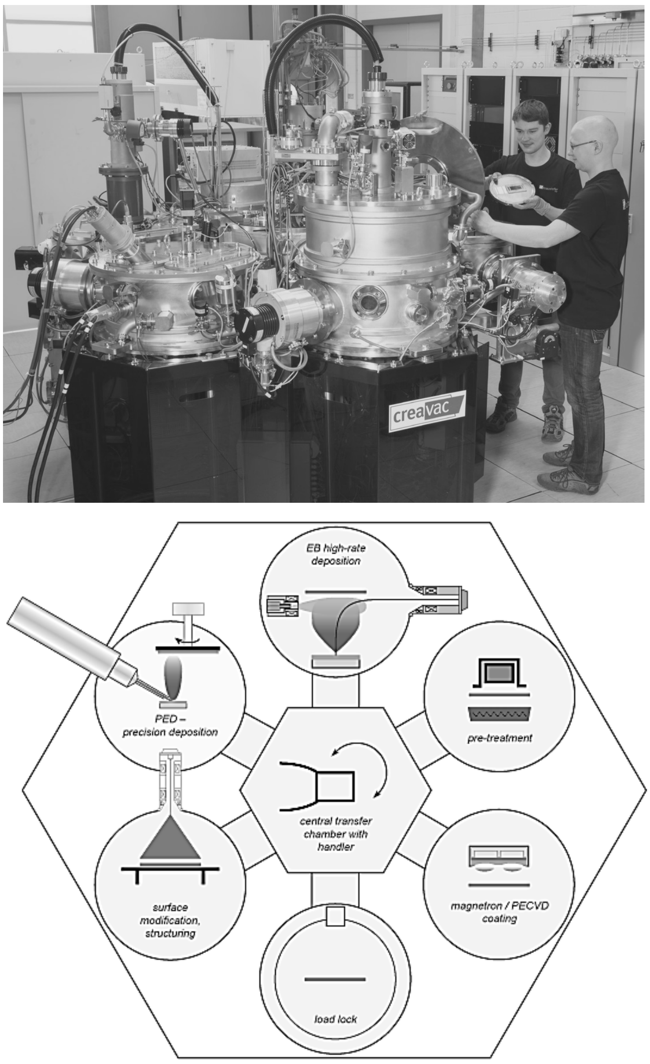


Fig.22. ERICA cluster tool instrumentation.

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REFERENCES

[1] H. Morgner, M. Neumann, S. Straach, M. Krug. The hollow cathode – a high performance tool for plasma activated deposition. Surf. Coat. Technol., vol. 108/109, 1998, pp. 513-519.

[2] H. Morgner, G. Mattausch, Chr. Metzner, M. Junghaehnel, R. Labitzke, L. Klose, T. Werner, J. Kubusch. Device for generating a hollow cathode arc discharge plasma. WO 2013/091927 Al.

[3] H. Wadley, G. Mattausch, H. Morgner, F.-H. Roegner. Coaxial hollow cathode plasma assisted directed vapor deposition and related method thereof. WO 2010/099218 A1.

[4] F. Fietzke, H. Morgner, S. Guenther. Magnetically enhanced hollow cathode – a new plasma source for high-rate deposition processes. Plasma Process. Polym., vol. 6, 2009, pp. S242-S246.

[5] F. Fietzke, B. Zimmermann. Plasma characterization and technological application of a hollow cathode plasma source with an axial magnetic field. Surf. Coat. Technol., vol. 205, 2010, pp. 1491-1496.

[6] J.-P. Heinß, V. Kirchhoff, L. Klose, Chr. Metzner, H. Morgner, B. Scheffel. Device for the pre-treatment of substrates. EP 2 087 503 B1, 2007.

[7] J.-P. Heinß. High-Rate Sputter Etching by using Hollow Cathode Arc Discharge for Metal Strip Coating. AEPSE 2011, Dalian, China.

[8] B. Zimmermann, F. Fietzke, H. Klostermann, J. Lehmann, F. Munnik, W. Möller. High rate deposition of amorphous hydrogenated carbon films by hollow cathode arc PECVD. Surf. Coat. Technol., vol. 212, 2012, pp. 67-71.

[9] S.V. Denbnovetsky, V.G. Melnyk, I.V. Melnyk. High-voltage, glow-discharge electron sources and possibilities of its application in industry for realizing different technological operations. IEEE Transactions on Plasma Science, vol. 31, 2003, pp. 987-993

[10] P. Feinaeugle, G. Mattausch, S. Schmidt, F.-H. Roegner. A new generation of plasma-based electron beam sources with high power density as a novel tool for high-rate PVD. Society of Vacuum Coaters 54th Annual Technical Conference Proceedings, Chicago, 2011, pp. 202-209.

[11] G. Müller, M. Konijnenberg, G. Krafft, and C. Schultheiss. Thin Film Deposition by Means of Pulsed Electron Beam Ablation. in: F.C. Matacotta and G. Ottaviani (eds). Science and Technology of Thin Films. World Scientific Publishing Co. Pte. Ltd., 1995, pp. 89-119.

[12] D. Yarmolich, P. Nozar, S. Gleizer, Y.E. Krasik, G. Mittica, C. Ancora, A. Brillante, I. Bilotti, and C. Taliani. Characterization of Deposited Films and the Electron Beam Generated in the Pulsed Plasma Deposition Gun. Japanese Journal of Applied Physics, vol. 50, 2011, 08JD03.

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