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Hollow cathode and hybrid plasma processing

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Abstract

Generation and features of the radio frequency (rf) hollow cathode discharge (HCD) and its transition into the hollow cathode arc (HCA) are described. Rf linear hollow cathodes for generation of plasma over large areas and suitable for further scale-up are presented. Examples of surface processing and coating by PVD, both by HCD and HCA, are given. The hybrid reactor, combining hollow cathode and microwave plasmas, integrates features of both and provides more options to control plasma characteristics and consequently properties of deposited films. The rf hollow cathodes can be operated in both, PVD and PE CVD regimes, depending on process parameters. These regimes can even be combined within one process. New concepts of fused hollow cathode (FHC), microwave antenna (MWA) and Hybrid hollow electrode activated discharge (H-HEAD) cold atmospheric plasma sources are introduced. The FHC with its modular concept can be used for gas conversion, cleaning and for surface treatment of temperature-sensitive materials at ambient atmosphere. The H-HEAD cold atmospheric plasma source, capable of generating plasma plumes more than 15 cm long, enables treatment of 3-d and complex geometry objects even at low gas flows.

Keywords: Hollow cathode; Linear hollow cathode; Hollow cathode processing; Cold atmospheric plasma; Fused hollow cathode; Hybrid plasma; Pulsed power; Air plasma

1. Radio frequency (rf) hollow cathodes

1.1. Rf hollow cathode discharge and hollow cathode arc

The radio frequency hollow cathode plasma jet (RHCPJ) in a coaxial arrangement for gas activation and deposition of coatings was patented in 1985 [1]. The cylindrical hollow cathode serves simultaneously as a feed gas inlet, see Fig. 1. Above a power threshold, which depends on the type of the gas and the cathode material [2,3], the breakdown of plasma-sheath boundary takes place and the discharge is forced out from the electrode, thus forming a very expressive plasma channel. This highly activated near afterglow region is the most important part of the hollow cathode discharge (HCD). When the temperature at the electrode is high enough for thermionic emission, the discharge is transformed into the hollow cathode arc (HCA). The HCA is a hot cathode/diffuse arc, contrary to the arc with cold cathode and cathodic spots.

Fig. 2 shows a typical *V–I* characteristics of the hollow cathode. The breakdown of the plasma-sheath boundary is accompanied by a drop of the voltage. The HCD is developed. At the transition of the HCD into the HCA, a decrease of voltage takes place again. The negative slope in the *V–I* characteristics is typical for the arc regime. The power dependence showing both the generation of the HCD and the transition from the HCD into the HCA was to our knowledge published for the first time [2] for the rf hollow cathode and the nitrogen discharge.

The hollow cathode is a versatile plasma source for both PVD, PE CVD and etching/cleaning processes. In PVD the cathode is a supply of metal particles, in PE CVD the gas is dissociated effectively at relatively low powers thereby enabling extremely high deposition rates (e.g. up to 1000 μm/min for Si–N and a-Si:H [4], 20 μm/min for microcrystalline carbonaceous films with high content of sp^3 bonds [5]). The deposition rates achieved for PVD are

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Fig. 1. Photograph from the argon RHCPJ discharge.

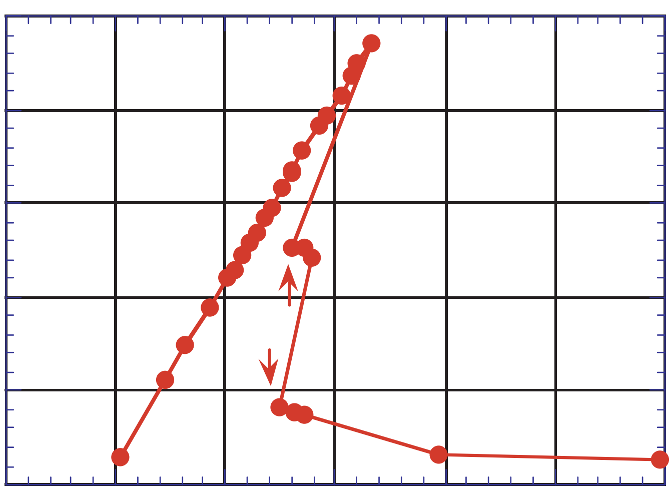

Fig. 2. *V–I* characteristics as measured for the RFHCPJ with cylindrical Ti electrode. Nitrogen flow of 100 sccm, pressure of 67 Pa (0.5 Torr). Transition points marked by arrows.

for example 2 μm/min for TiN [6] or up to 4 μm/min for CrN [7].

1.2. Large area processing

The first design of a linearly scalable source, the linear arc discharge (LAD) source [8] was based on an rf-generated hollow cathode discharge between two parallel plates with a confining magnetic field. The confining magnetic field perpendicular to the cathode plates promotes the pendulum motion of hot electrons between the plates and facilitates the hollow cathode effect, simultaneously providing high power density. The linear hot zones are formed at the plate surfaces due to an ion bombardment inside the hollow cathode. The shape and position of the linear hot zones depends on the magnetic field configuration.

In order to ensure a uniform release of the material along the slit, a new concept, the magnets-in-motion (M-M) arrangement in the rf linear hollow cathode system, was introduced. The static magnets are either replaced by or combined with the rotary permanent magnet systems [9,10]. Fig. 3 shows the most simple arrangement, with two permanent magnet systems placed opposite to each other and a driver system for moving the magnet systems. Experimental results show that the discharge characteristics respond to the character of the motion. The M-M source, with time and space controlled discharge reminds a special sequentially pulsed plasma.

The M-M rf linear hollow cathode can be used for a variety of deposition processes, both in the HCD and HCA regimes. Several processes, developed for the RHCPJ were successfully scaled up for the M-M plasma source, e.g. TiN, TiO_2 and AlN reactive depositions [11].

The effect of special mixtures of nitrogen with argon for the titanium rf hollow cathode was already reported in several papers, see [6,12]. At low nitrogen content in argon, the quenching of argon metastables by nitrogen molecules brings about a thermal energy gain, promoting the transition of the process into the HCA regime. At low

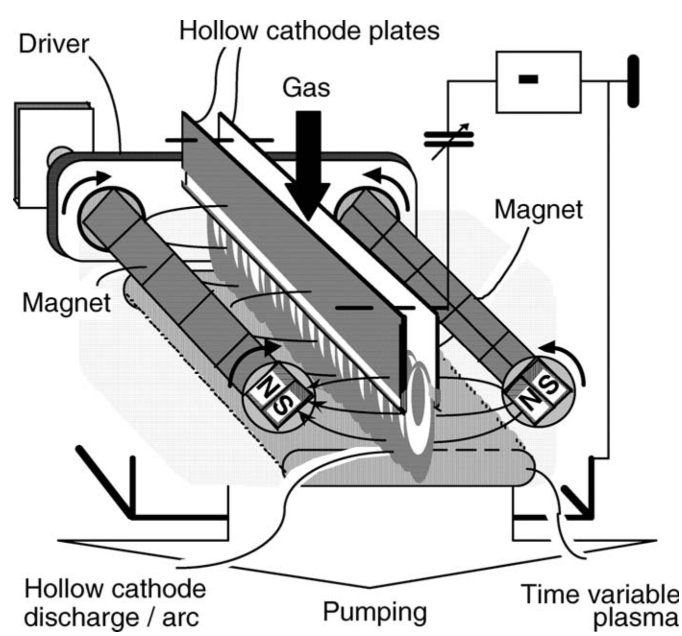

Fig. 3. Schematic sketch of the magnets-in-motion (M-M) rf linear hollow cathode source.