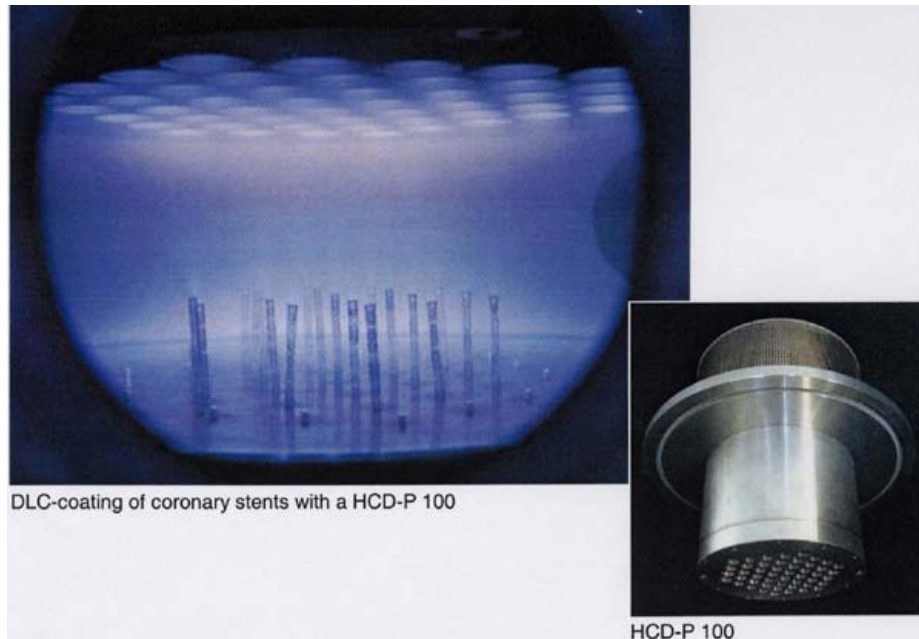


13.56 MHz Hollow Cathode Plasma Source by PlasmaConsult



Features

- Operation over an extended power range
- No mode jumps
- High plasma and radical densities with excellent axial homogeneity
- Compatible with chemically reactive and nonreactive gases
- cw and pulse operation
- Low contamination
- scaleable

Applications

- Plasma-enhanced chemical vapor deposition (PE-CVD)
- Plasma polymerisation
- Surface modification
- Plasma cleaning
- Plasma etching
- Reactive and non-reactive ion etching
- Materials Science (in general)



General

Hollow Cathode Discharges (HCD) represent a very effective and yet comparatively simple, cost effective means of high density, low temperature plasma generation.

The Hollow Cathode Effect

Consider two parallel metallic plates in a vacuum chamber filled with a low pressure gas. For a given plate separation d and pressure p there exists an optimum product $p \times d$ such that the plasma ignition voltage (or power) becomes minimum (so-called PASCHEN-Law). This voltage is applied to the two plates one of which is usually grounded (often being the vacuum chamber wall). A plasma excited in such a way has a comparatively low density being insufficient for advanced plasma processing.

If the negatively biased electrode is formed as a cavity or cylindrical cathode structure (as for the HCD-P) the conservation of particles and photons leads to drastically increased ionization and/or emission.

To understand the working principle it is in order to look a little closer to the underlying physics. Usually the so-called plasma potential is the most positive of the whole set-up including the vacuum chamber walls. As a consequence the negatively charged electrons tend to be confined to the plasma. To be more precise, this holds only for the lower energy electron population representing a substantial fraction of all electrons.

In the hollow cathode a negatively biased cavity or cylindrical tube encloses the plasma (Fig. 1). Electrons within this plasma are constantly being repelled when approaching the hollow cathode walls : An oscillatory motion of the electrons results yielding greatly improved ionisation rates and thereby higher plasma densities.

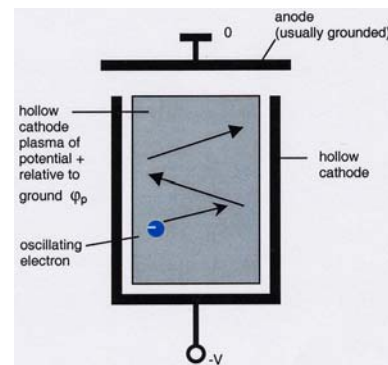


Fig. 1 Principle of a dc-hollow cathode discharge.

The discharge is driven by direct current (dc). In the remote plasma processing mode the hollow cathode plasma shown is often referred to as the “primary” plasma.



Functional Principle

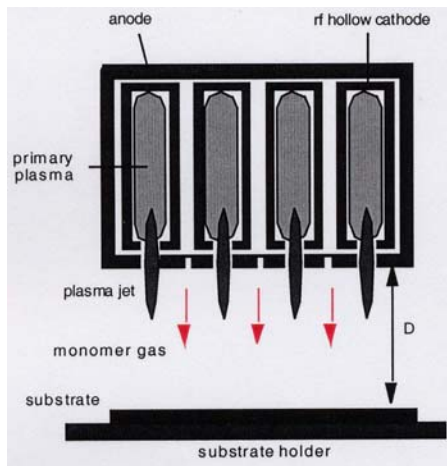


Fig. 2 Functional principle of the plasma polymerization with HCD-P.

The plasma jets (consisting of electrons, ions and excited neutrals/radicals) interact with the monomer fed into the system by another matrix of 48 orifices, located between the plasma jet outlets. At a distance D downstream the plasma jets the substrate is positioned. Ultraviolet light in combination with the jet-particles initiate the polymerisation process taking place at the substrate surface.

DC versus rf-hollow cathode discharges

Fig. 1 relates to a dc-hollow cathode discharge. The de-power coupling works very well when using only chemically non-reactive gases such as argon (Ar) or helium (He). However, the addition of film forming monomers possibly blocks the de-current flow after a thin, electrically non-conducting polymer film forms on one of the source electrodes. As a consequence, the dc discharge may be extinct. RF excited discharges as the HCD-P are much more insensitive to these unwanted contaminations. Furthermore, due to the specific capacitive coupling used a well balanced and symmetric power flow is guaranteed for each individual plasma jet.

Concept of the HCD-P

The plasma source HCD-P employs the hollow cathode effect as described above.

Fig. 2 shows four plasma jets of the hexagonal matrix of 48 jets. The inner tubes are rf-powered enclosing the primary plasma; the outer part of the source is electrically grounded. 48 hollow cathode cylinders are arranged in a hexagonal matrix forming the high intensity primary plasma jets.

The hollow cylinders are electrically isolated from the housing. They are connected to the rf-power generator; the housing is grounded..

A proprietary compact gas distribution system (primary gas monomer) featuring fractal geometry gas channels plus a proprietary internal cathode structure guarantees a homogenous jet formation over extended source dimensions.

The material used is all-aluminium important for a good thermal conductivity and reduced surface loss rates when working with radicals and excited species. Depending on the technological needs the whole system can be operated isothermally by adjusting the cooling/heating water-temperature.

Performance

There are two major parameters controlling the performance and technical applicability of hollow cathode plasma sources such as the HCD -P. These are the working pressure range of the hollow cathode (primary) discharge and the rf-power required for plasma breakdown, i.e. ignition. Typical data for an atomic (e.g. argon) and a molecular gas (e.g. oxygen) are given below.

For oxygen the same definition and arguments hold in principle as in the case of argon. However, because of different physical energy absorption mechanism in a molecular gas the actual data change.



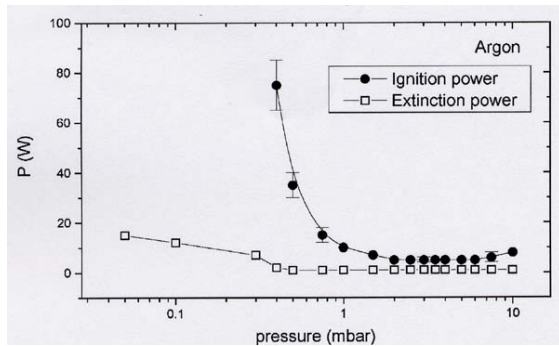


Fig 3. Argon-plasma excitation in a HCD-P.

Shown is the pressure dependent minimum rf-power required for ignition of all plasma jets (gas flow 400 sccm). As can be seen from the data there exists a distinct power minimum in the pressure range from about 2 to 8 mbar defining the so called mbar-processing window. Also shown is the minimum rf-power required to maintain a stable discharge. As can be seen this power is extremely low allowing, e.g. temperature sensitive substrates to be treated as well as polymer deposition with a high degree of monomer retention (in this case the argon plasma is used as primary plasma interacting with a monomer injected downstream).

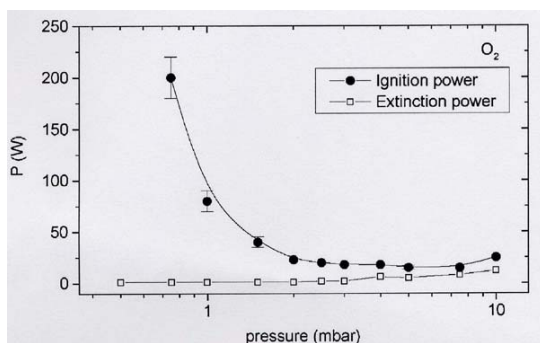


Fig. 4 Oxygen plasma excitation in a HCD-P.

Shown is the pressure dependent minimum rf-power required for homogeneous ignition of all plasma jets (gas flow 200 sccm). Compared to Ar-plasma the operating pressure range is similar, however the rf-power needed for plasma ignition is significantly higher while the minimum power needed for homogeneous plasma operation is extremely low as well.

Once the plasma is excited the rf-power can be varied over an extended power and pressure range without affecting the stability of the discharge and overall plasma jet formation. When further reducing the rf-power there is a minimum below which the plasma no longer can be maintained.

Extinction, defined as the minimum power required to maintain a stable discharge.

Plasma density

The Ar-ion density, measured by a double Langmuir probe system also manufactured by JE PlasmaConsult GmbH, downstream the plasma jets at a position of 40 mm from the anode orifices is shown in Figs. 5 to 8.

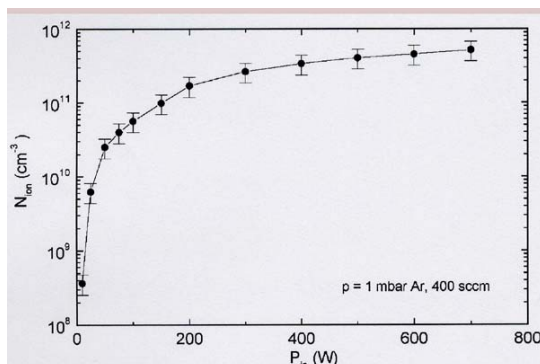


Fig. 5 Plasma density in an Ar-plasma as a function of rf-power.

The density can be varied over 2 orders of magnitude and exceeds $3 \times 10^{11} \text{ cm}^{-3}$ at rf-powers $> 400 \text{ W}$ (position 40 mm downstream, 1 mbar Ar, gas flow 400 sccm).



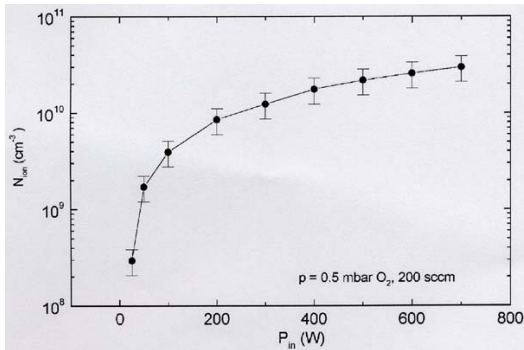


Fig. 6 Plasma density in an O₂-plasma as a function of rf-power.

The density can be varied over 2 orders of magnitude and exceeds $1 \times 10^{10} \text{ cm}^{-3}$ at rf-powers > 400 W (position 40 mm downstream, 0.5 mbar O₂, gas flow 200 sccm).

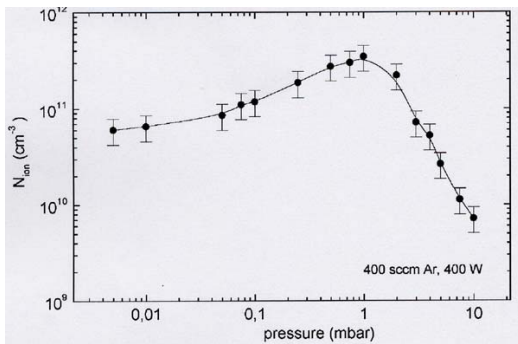


Fig. 7 Plasma density in an Ar-plasma as a function of pressure.

The HCD-P can be operated over 2 orders of magnitude of pressure. The plasma density exceeds 10^{11} cm^{-3} for pressures between 0.01 mbar and 2 mbar (position 40 mm downstream, $P_{\text{rf}} = 400 \text{ W}$, gas flow 400 sccm).

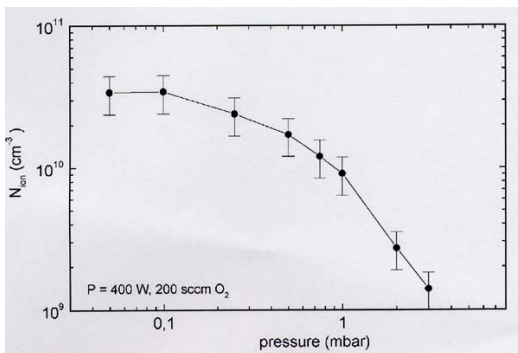


Fig. 8 Plasma density in an O₂-plasma as a function of pressure.

The HCD-P can be operated over 2 orders of magnitude of pressure. The plasma density exceeds 10^{10} cm^{-3} for pressures between 0.05 mbar and 0.75 mbar (position 40 mm downstream, $P_{\text{rf}} = 400 \text{ W}$, gas flow 200 sccm).



Homogeneity Issues

The achievable film homogeneity and quality in plasma polymerisation is controlled by the substrate distance to the monomer inlet and jet-orifices (primary plasma). Another important influence relates to the total gas flow patterns. Detailed experimental investigations have shown that a distance of about 60 mm between the plasma jet outlets and the substrate is a good compromise between the desired film homogeneity and achievable deposition rates.

As an example for a low-temperature PE-CVD process with the HCD-P DLC-deposition on a substrate has been performed. High quality DLC films were grown at room temperature with a film uniformity better than 4% across a 4" Si-wafer (substrate bias at -400 V).

In summary the HCD-P yields excellent homogeneities in plasma-induced surface modifications/activations as well as in plasma polymerised thin films.

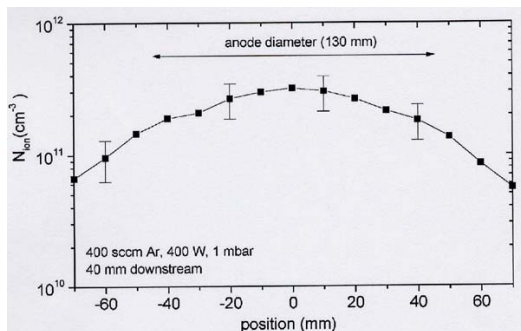


Fig. 9 Radial ion distribution of the HCD-P

(position 40 mm downstream, $P_{rf}=400$ W, pressure 1 mbar, gas flow 400 sccm).

The data are taken downstream the plasma-jets at a position of 40 mm from the anode-orificies. Position 0 is the centre of the source.

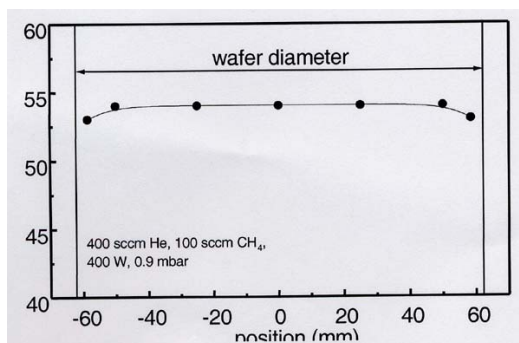


Fig. 10 Film thickness (nm)

($P_{rf}=400$ W, pressure 0.9 mbar, gas flow 400 sccm He, 100 sccm CH_4).



Applications

The HCD-type sources has been used very successfully in the fields mentioned above, especially for

- plasma polymerisation,
- plasma-enhanced chemical vapour deposition (PE-CVD), e.g. SiO_x , Si_3N_4 , DLC, fluorocarbon thin films,...
- etching, e.g. removal of DLC,...
- surface modifications, e.g. controlling free surface energy, adhesion, wet ability, paint ability,...

Lifetime

The HCD-P is manufactured using exclusively aluminium and ceramic parts for electrical insulation. No quartz windows etc. are necessary. Since all ceramic parts are shielded from direct plasma interaction and sputtering the source is extremely robust and offers extended lifetimes often superior to those of inductively and microwave excited plasmas.

Contamination

It is commonly said that HCD's are prone to unwanted parasitic sputtering of the source electrodes. Due to its proprietary and patented excitation geometry PlasmaConsult's hollow cathode plasma sources HCD enclose the plasma completely with the exception of the plasma jet holes. Any possible contamination must have its origin in the inner cylinder or at the jet orifices.

From the source geometry it is highly unlikely that contaminants (in this case aluminium) will leave the inner source and are deposited e.g. on a substrate.

In fact, after two hours of operation (300 sccm Ar, 1 mbar, 400 W), the surface concentration of aluminium on a Si-wafer was found to be 0,25 of the Si concentration only.

Technical Data

- Pressure range 10 – 1000 Pa
- rf power 1 –700 W, 13.56 MHz
- Cooling water
- Mounting flanges DN 250 ISO-KF or larger
- Mass flow rate 5 –500 sccm (primary gas)
- Mass flow rate 4 –100 sccm (monomer)

