Industrial plasmas in academia

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Abstract

The present review, written at the occasion of the 2014 EPS Innovation award, will give a short overview of the research and development of industrial plasmas within the last 30 years and give a first glimpse into future developments of this important topic of plasma physics and plasma chemistry. In the present contribution some of the industrial plasmas studied at the CRPP/EPFL at Lausanne are highlighted and their influence on modern plasma physics and also discharge physics are discussed. One of the most important problems is the treatment of large surfaces such as used in solar cells, but also in more daily applications such as the packaging industry. In this contribution the advantages and disadvantages of some of the most prominent plasmas such capacitively- and inductively-coupled plasmas are discussed. Electromagnetic problems due to the related RF and its consequences on the plasma reactor performance, and also dust formation due to chemical reactions in plasma, are mentioned. Arcing and parasitic discharges occurring in plasma reactors can lead to plasma reactor damages. Some specific problems such as the gas supply of a large area reactor are discussed in more detail. Other topics of interest have been DC discharges such as used in plasma spraying where thermal plasmas are applied for advanced material processing. Modern plasma diagnostics make it possible to investigate sparks in EDM (Electrical Discharge Machining), which surprisingly show properties of weakly coupled plasmas. Nanosecond DBD (Dielectric Barrier Discharge) plasmas have been applied to more speculative topics such as applications in aerodynamics, and will surely be important in future ignition and combustion.

Most of the commonly-used plasma sources have been shown to be limited in their performance. Therefore new, more effective plasma sources are urgently required. With the recent development of novel resonant network antennas for new advanced large area or large volume plasma sources, an important step towards high performance plasmas and new fast processes is made.

1. Introduction

Plasma processing has proven to be an important tool in industry. Many of our present-day technologies and applications rely strongly on plasma processes. Without any doubt, plasmas have been at the origin of the overwhelming success of semiconductors and their application in electronics and communications. The upcoming very diverse industrial applications lead to the use of quite a large variety of plasmas. The classes of plasmas used in industrial applications differ substantially from plasmas such as fusion plasmas and astrophysical plasmas as typically investigated in academia. Thermal and, in most cases, non-thermal plasmas are applied for processing, running mostly in a chemically reactive environment. In particular, non-thermal plasmas are often used since they allow low temperature processing where normally high temperatures are needed. Efforts to understand the complex plasma physics and also plasma chemistry, together with investigating the surface physics taking place during processing, have been made in the recent years in academia but also to a certain extent in industry.

Interestingly, many of the problems encountered related to industrial plasma processing also lead to new fundamental topics in plasma research. One of the best-known examples of basic plasma physics research triggered by applications is complex (or dusty) plasma, since dust particles were found to influence the properties of the processing plasma and of the deposited films. Such (or similar) dusty or complex plasmas are also found in astrophysics and are therefore of fundamental scientific interest as well.

Very important industrial applications are the production of thin film solar cells, flat displays, architectural glass, and packaging, which require large area plasmas for deposition. Therefore, large area plasmas have been investigated in strong relation to their specific industrial exploitation. Basic investigations and development of large area plasmas are rarely reported in the literature. Large-scale plasmas often show a different behavior with respect to small laboratory plasmas, which are mostly edge dominated. Therefore, the necessary upgrade is in most cases a cumbersome task, since reactor and plasma parameters cannot simply be scaled up. In addition, process-specific parameters such as deposition rate and material properties also require highly uniform plasmas. An additional industrial demand is the reduction of individual processing time leading to plasmas with higher and higher radical densities. Therefore in future, versatile, high-density plasma sources will be in strong demand for modern plasma processing.

Many problems arising in large area plasmas are related to the large substrate sizes and the high electrical powers involved to drive the plasma. Electrical and fluid dynamic problems of the reactor and the complicated plasma chemistry contribute to the complexity of large area plasma reactor use.

The aspect of large area industrial plasmas is contrasted by other potential plasma applications such as the use of small but very dense plasmas for mechanical small-scale machining and the application of DC plasmas used in thermal plasma spraying for fast deposition of dense, thin films. Recently, plasmas have also entered into new applications and challenges as will shortly be demonstrated by some insight into the development of plasma for aerodynamics and the important field of combustion and ignition. Novel studies on resonant network antennas demonstrate the wide future potential of this new type of RF antenna for advanced applications in industrial processing.

In this paper, the different plasmas used for some typical industrial applications are presented and their properties are discussed. The most important problems in plasma processing investigated in academia will then be highlighted and some specific problems such as the working gas supply in large area reactors and its solution will be discussed in more detail. Future developments in industrial plasmas and related topics will be presented.

2. Industrial plasma sources

The choice of the plasma source is mainly dictated by the specific application. The use of plasmas in widespread applications leads to a large number of quite different methods of producing plasmas with parameters and properties demanded by the material processing. As shown in Fig.1, industrial plasma sources operate over a wide plasma parameter range. These plasmas are driven in gas pressures ranging from a few Pa up to atmospheric pressure. As a consequence, all different types of non-

equilibrium plasmas, but also often thermal plasmas, are found in industry. Industrial applications also lead to the use of plasma produced in a wide variety of gases, or even produced in liquids and solids. Besides noble gases, many types of molecular gases and even complex metal-organics are nowadays employed for plasma treatments. With the use of such different gases the number of possible plasma constituents is considerably increased. Plasmas sources are mainly conceived to optimize particular plasma species such as negative ions, radical or excited species depending on the process. Such plasma optimization needs a detailed understanding of the ongoing plasma physics and importantly also of the plasma chemistry.

One very specific application of plasmas in industry is thin film deposition by plasmas running in reactive gases. The deposition in general needs high throughput, homogeneous plasmas for uniform coating and a high degree of reproducibility. A very specific case is large area thin film deposition as used in solar cells, flat displays or in the packaging industry. The specifications for deposition plasma in the semiconductor domain will have quite different demands concerning impurity content from plasmas used for barrier coating in packaging. Therefore, the type of plasma reactor might imply quite different design and construction depending on the specific applications.

In the following, some of the problems and some solutions in large area depositions are discussed. Presently, various plasma sources for large area industrial applications are given in the literature [1]. For large area applications besides capacitively- and inductively-coupled RF plasmas, magnetron discharges are often applied [2]. In particular, magnetron plasmas are widely used in industrial roll-to-roll processing. Magnetron discharges, also since they are used for manufacturing of a large palette of products, are one of the best-investigated industrial plasmas.

Capacitively- and inductively-coupled plasmas used in the so-called batch mode have been upscaled from laboratory-sized plasmas to large areas of the order of several square meters [3]. Various modifications to the plasma source during upscaling, such as the use of a lens-shaped electrodes in capacitively-coupled plasma reactors [4] have been necessary to obtain sufficient industrial performance.

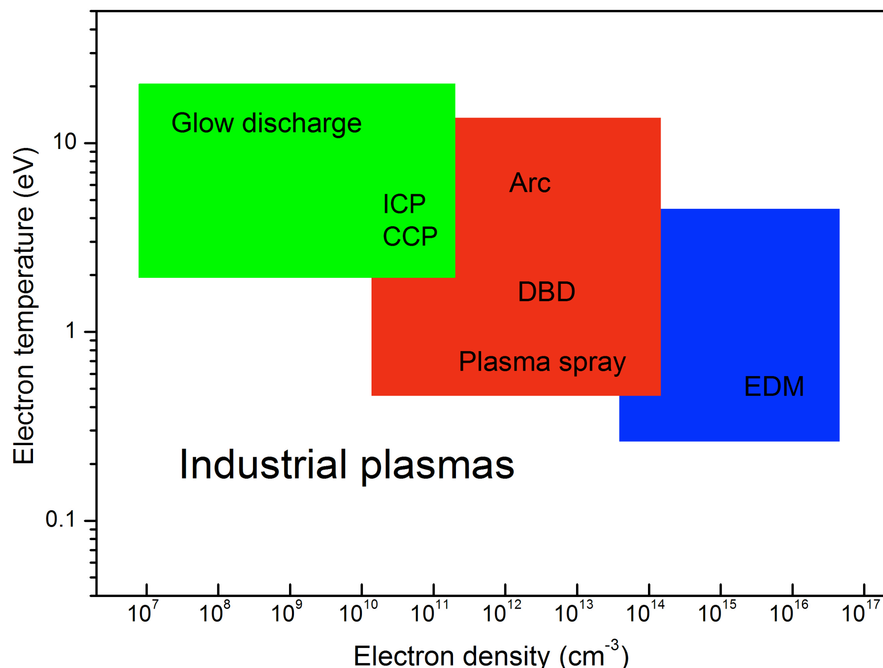

Fig. 1 Electron temperature and electron densities of industrial plasmas. The parameters of processing plasmas discussed in this paper are indicated.

One of the problems arising from upscaling of capacitive plasma sources to large sizes is due to the change in impedance with size: Increasing the size leads to an increased capacity of the reactor, and so the reactor presents a lower and lower impedance. Therefore, in the case of large area capacitively-

coupled plasma, a strong RF current flows in the input lines therefore requiring the construction of ruggedized RF transmission lines and RF feedthroughs. This tendency can give rise to further problems, since parasitic discharges can be triggered by faulty design of RF components if no precautions are taken.
On the other hand, upscaling of inductively-coupled plasmas leads to high voltages on the inductive device. Therefore the question of whether the plasma production is being more capacitively driven than inductively driven has to be considered. The installation of electrical screens to avoid parasitic capacitive coupling leads to further design complications of conventional inductive plasma sources.

In order to decrease the processing time, high plasma densities are generally demanded since high rate processing is closely related to rapid production of radicals. Various efforts have been undertaken to increase the overall efficiency of large area capacitively-coupled plasma reactors. However, it is believed that substantially higher deposition rates than presently achieved cannot be obtained with such a device. Higher particle densities can be obtained in inductively-coupled plasma and even higher densities only in wave-excited plasmas such as in helicon devices. Recently, large efforts have been made in order to advance these plasma sources for high deposition rate processing.

In many different applications of the growing layer or for the treated surface the resulting ion bombardment from the plasma is of great importance to obtain desired material properties. For instance, this is the case in the production of thin film silicon layers for solar cells where most probably a modest ion bombardment of the growing layer is necessary for device quality material. Various modifications of plasma reactors or processing methods have been developed to control the ion bombardment energy. One way to obtain a controllable ion bombardment is by applying different RF frequencies in a capactively-coupled device [5]. In inductively-coupled plasmas a control of the ion energy is obtained by biasing an additional electrode by means of a DC or an additional RF power.
Sources which are completely different from the discussed inductively-coupled (ICP) or capacitively-coupled (CCP) plasmas are used for applications in aerodynamics and for plasma assisted combustion. For these applications, AC dielectric barrier discharges (DBD) discharges run at ambient atmosphere are used and recently the more promising nanosecond DBD discharges have been tested [6]. Plasma actuators for flow control made of such dielectric barrier discharges have the advantage with respect to conventional flow actuators of a simple design, low mass, large frequency bandwidth, the absence of moving parts and they allow real–time feedback control. The control mechanisms of the AC DBD and of the nanosecond DBD discharge differ fundamentally. In the case of the AC DBD discharge, the ion wind produced interacts with the boundary layer. This ion wind is presently limited to about 10 m/s, a value too low for real aerodynamic applications. The nanosecond DBD discharges are known to excite a compression wave. At present it is thought that the control capability of this plasma actuator does not originate from electro-hydrodynamic flow acceleration but from the excitation of flow instabilities by the compression wave generated by the Joule heating of the DBD discharge. Depending on the application, control of the leading edge separation on a profile could be obtained up to about 60 m/s. Flow control might be possible in the future after more intense investigations and development of the interaction of the plasma with the high velocity flow. It has to be mentioned that for the nanosecond pulsed DBD, fast high voltage power supplies are necessary. For control tests, such power supplies small enough to fit into a model aircraft have been constructed and, by carefully avoiding electrical disturbances, used for flow control. The development of small and light high voltage pulse generators is also important for other applications of atmospheric DBD such as in medicine and in particular also for the widespread applications in combustion and ignition [7].
All the previously described plasmas belong to the group of non-thermal plasmas. A very typical application for thermal plasma is the well-established plasma spraying. Classical plasma spray is performed at atmospheric pressure or in a low vacuum environment with the aim of reducing oxidation of the coating. Plasma spraying finds large success in applications such as automotive and avionics. In plasma spraying, small powder particles are introduced into the plasma, which melt and finally splash onto the substrate forming a mostly porous, thick layer. At high operation pressures essentially solid precursors are used whereas for liquid and gaseous precursors the plasma torch parameters have been optimized at intermediate or low pressure. In this low-pressure range, and with liquid or gaseous precursors, the chemistry within the plasma starts to play an essential role [8]. This

latter process has to be distinguished from the so-called reactive plasma spraying where reactive gases are added in order to modify the powder particles. In reactive thermal plasma chemical vapor deposition (CVD), the precursors are evaporated and the gaseous components contribute to the plasma chemistry and coating. With this new low pressure process the high porosity of the plasma spray coatings has been overcome and dense layers at high deposition rate, similar to the films of non-thermal plasmas have been obtained. Due to the high enthalpy in the plasma, the thermal plasma CVD is more efficient than the widespread RF plasma processing. In particular, due to liquid and solid precursors, higher throughput and higher deposition rates than in RF plasmas are obtained [9]. With this process development it is possible to obtain a variety of coating qualities at high rate using the same plasma tool.

3. Problems of industrial plasmas

The problems encountered in industrial plasma devices are related to different topics in science and engineering. The large variety of problems found in the case of large area capacitively-coupled RF plasma reactors [1] are summarized in Fig.2. These or similar problems are also found in other types of plasmas used in industry.

Unfortunately, many of the problems considered arise from improperly designed hardware such as the geometry of the plasma reactor, the incorrect implantation of the RF power connection(s) or poor vacuum-compatible reactor design. The most well-known difficulties arise from electrical problems and are related to RF. Additional difficulties can arise from substrate charging during processing, making substrate handling more difficult since electrostatic discharges have to be avoided [10]. The gas supply and pumping design can have a very large influence on the properties of the obtained layers, whereas various plasma properties such as chemical reactions in many reactive plasmas can lead to dust formation causing several problems for the substrates and can lead to strong contamination of the reactor. In the following some of these topics shall be discussed in more detail.

The standing wave effect in large area capacitively-coupled plasmas leads, as is widely known, to electric field non-uniformity and consequently inhomogeneous deposition. This effect has been corrected by a more complex electrical design of the plasma reactor. Lens shaping of the RF electrode is one of such designs to compensate the size-induced standing wave effect [3,4]. Further electromagnetic effects with asymmetric electrodes lead to inhomogeneity at the plasma edge thus reducing the effective usable size of the substrate [11,12]. As it turns out, the details of the RF feeding of the electrode are also important and also influence the deposition. To demonstrate the importance of design details of the plasma reactor, it has to be mentioned that small changes in the reactor capacity due to a small hole in an electrode already leads to visible inhomogeneity in the coating.

The large area of the reactor might also strongly influence the contamination of the growing layers. This is in particular important in the case of semiconductor production such as for thin film silicon deposition for solar cells. The contamination problem can be solved in various ways by the design of the plasma reactor, for example, with the differentially pumped plasma box concept [3].

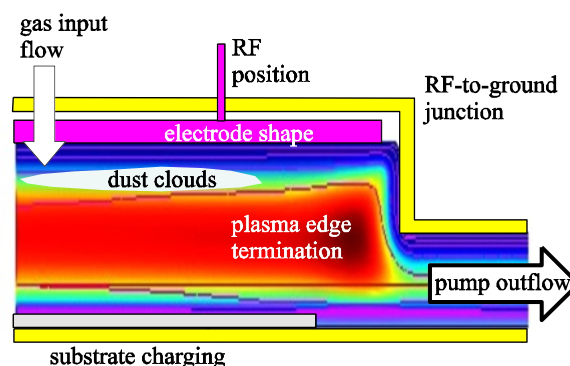

Fig.2 Schematic of a generalized, large area capacitively-coupled RF reactor. The labels show some possible design difficulties mainly associated with large area plasmas.

A very important problem in deposition reactors is the gas supply and the pumping of the plasma reactor [13]. This problem will be treated here in more detail.
Fig. 3 shows a schematic of a rectangular RF capacitive reactor with lateral pumping on two opposite sides and a uniform showerhead gas inflow through one of the electrodes. The pressure is uniform over the whole reactor, to a good approximation, provided that the electrode gap is not too small because the pressure gradient is proportional to the inverse cube of the gap distance. For these conditions, the gas transport is described by finite-gap stagnation point flow [13] whose similarity solution exhibits lateral uniformity. In the approximation of creeping flow, relevant to most plasma deposition processes, the vertical flow velocity has a cubic vertical profile but is independent of lateral position, whereas the horizontal flow velocity is proportional to distance from the mid-point, and has a parabolic vertical profile. The resulting velocity field is shown by the streamlines in Fig. 3 for this example case of plasma deposition; the deposition rate onto the growing film surface is represented by a non-zero fluid velocity into the walls known as Stefan flow. The key property of stagnation point flow is that the fluid vertical flow velocity and the concentrations of all species are independent of lateral position.

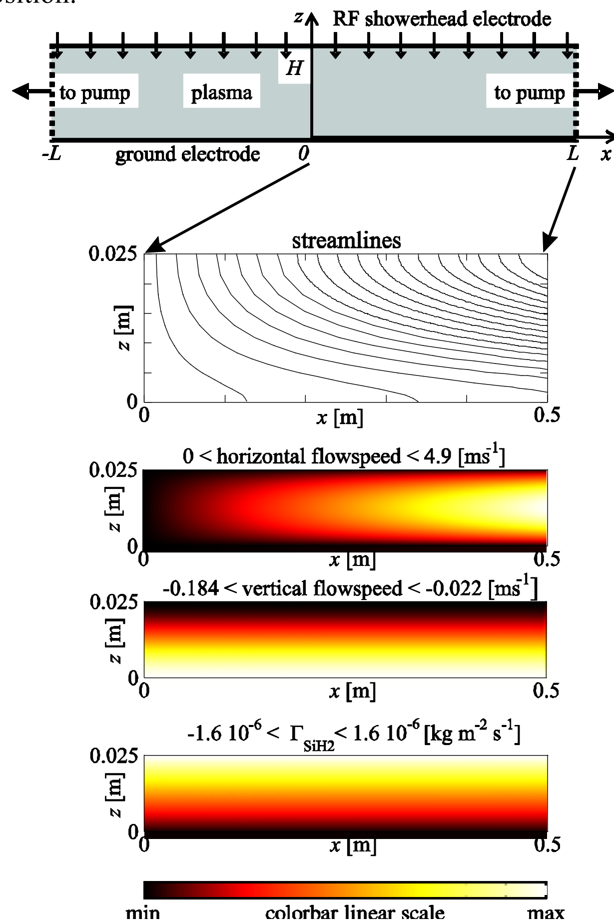

Fig. 3 Schematic of a rectangular showerhead reactor, showing the numerical solution of the gas flow streamlines in the right half. The surface plots show the horizontal and vertical flow speeds and the diffusive flux of SiH_2 for an example case of plasma deposition.

This implies that the convective and diffusive flux, and therefore the net flux of each species, is uniform over the whole substrate area, as shown by the lateral uniformity in the numerical solutions of Fig. 3. This results in the desired uniform deposition rate on the substrate. This stagnation flow solution holds for rectangular reactors with lateral pumping through one entire side, or two opposed entire sides, and for cylindrical reactors with uniform circumferential pumping.

Another important problem in reactive plasmas is the formation of nanoparticles. Besides the damage that particles can cause in the thin film, dust can also lead to inhomogeneity of the deposited

layer. The localised powder cloud changes the local RF power density in the plasma and consequently inhomogeneous films originate. Dust reduction or elimination is a complex problem involving plasma chemistry as well as reactor design. To solve this problem the dust formation due to volume reactions in reactive plasmas had to be understood, leading to the opening of a new topic: complex or dusty plasmas.

The presence of nanometre particles was first observed in etching devices [14] triggering research into the origin and behavior of particles in low-pressure plasmas. Later, abundant particle formation was found in hydrocarbon and silane plasmas, which are used for many important industrial applications. The powder formation in capacitively-coupled RF silane plasmas was extensively investigated in order to find the powder precursors and the responsible gas phase reactions leading from the SiH_4 gas to nano- or micrometre sized particles [15]. Mass spectrometry in these capacitively-coupled RF silane plasmas revealed no high mass neutrals nor positive ions, but high mass anions are produced. Anions up to a mass of 1600 amu containing up to 60 silicon atoms have been found in these plasmas [16]. In the case of RF silane plasmas, anions play an important role as precursors for nucleation, since they have a long dwell time in the plasma due to trapping in the plasma sheath [17]. During the cluster growth or nucleation, the charge of the small particles fluctuates between neutral or singly-charged anion clusters. This charge fluctuation allows agglomeration and coagulation of the precursors into macroscopic particles bearing multiple negative charges, which in turn are trapped within the plasma. These particles can increase in size by neutral particle accretion to become micrometre-sized particles, which behave in a similar way as has been shown in numerous so-called dusty plasmas experiments.

Powder formation in other reactive plasmas containing metal- or silicon-organic precursors such as for the deposition of SiO_x (for packaging) and diamond-like carbon are also found and can represent serious restrictions to the process.

Finally, a very serious and often not very much investigated problem in plasma processing is the reproducibility and plasma parameter variations from device to device. One other important problem in industrial plasmas is related to uncontrolled arcing and the formation of parasitic discharges. The latter problem can have expensive consequences, since in plasma reactors RF power levels of several kilowatts can be involved. A small fraction might go undetected into an arc or other parasitic discharge, which in turn could lead to serious damage of the reactor. Many different types of parasitic discharges and arcing can occur in an industrial reactor. The occurrence of these discharges is strongly dependent on the design or geometry of the plasma reactor and depends also on the process parameters such as pressure and power. Precise monitoring of the input power and the matching condition, and a consequent power limiting control can suppress arcing events, however a good understanding of discharge physics is necessary to avoid or at least retard arcing. For these reasons, a few of the typical situations often encountered in large area plasma reactors have been investigated in experiments simulating the situation in real industrial reactors [18]. Such investigations turned out to be very efficient to improve process reliability. Another phenomenon related to parasitic discharges, so-called plasmoids, were recently investigated in detail. When a plasmoid forms in the hole of an electrode, it transports electrons through to the reverse side, for instance, of a pumping grid in a large area reactor, which is meant to contain the plasma. It was found that plasmoids are actually sustained by the radio-frequency plasma potential, forming a positive plasma potential on both sides of a grid in the reactor. It is the funneling of an intense electrical current that can cause strong heating of the plasmoid and subsequent damage to the reactor components [19].

Besides arcing in plasma reactors, arcing is a serious issue in many technical devices. In particular in the miniaturisation of equipment and of electronic device, the small dimensions can lead to electrical breakdown and finally to discharges which can be dangerous for the devices. Arcing in industrial devices is a serious problem for the safety of personnel and equipment. One example that has been investigated in collaboration with industry and ESA is arcing phenomena in spacecraft equipment. Arcing in spacecraft can put an entire costly mission at risk, therefore arcing - in particular in the power supply section - must be avoided by all means. The approach is to study experimentally and theoretically the susceptibility of specific components to electrical breakdown [20]. Breakdown experiments are performed on the original piece or importantly also using models of principal parts of the equipment under test. Numerical simulations of breakdown of these complex three-dimensional geometries have been made in order to understand electrical breakdown in complex geometries. A

basic understanding of breakdown in complex geometries can be obtained from such investigations, and safer equipment can be designed. Such new physical rules are complementary to the well-known Paschen law which applies only to the ideal case of breakdown between plane parallel plates.

4. Plasma diagnostics and simulation in industrial plasmas

Diagnostics in large area plasmas or in industrial plasmas has several aims. Firstly, plasma diagnostics serve as process monitoring of the most important parameters of the plasma and the reactor. Furthermore, plasma diagnostics are necessary to monitor reproducibility of the process but also for transferring plasma parameters from reactor to reactor in equipment manufacturing. The application of plasma diagnostics in an industrial environment also requires efficient, cheap, robust and simple diagnostics, which can withstand high temperatures, vacuum, and chemical attack.

It turned out that in industry only a few plasma diagnostics are available, not only due to the cost but also because of the complexity of using diagnostics in an industrial environment. However many sophisticated plasma diagnostics are available in academia, including trained personnel for interpretation, which are of great help to the research made in industry.

Most recent developments have been performed in testing the coatings resulting from the plasma. Layer thickness or the important deposition rate, material properties and also the homogeneity of the film or of the required functionality produced by the plasma are determined by various often time consuming ex-situ measurements. In-depth diagnostics of large area plasmas are only rarely performed due to the poor access to the large area plasma and the few existing plasma diagnostics adapted to large area plasma reactors.

The most common diagnostics are measurements of process relevant parameters such as gas pressure and RF parameters. Electrical parameter measurements are necessary to monitor the process and to detect parasitic discharges to protect the equipment from dangerous electrical arcing.

Various types of spectroscopy such as emission spectroscopy and imaging using CCD cameras are applied to investigate large area plasmas. FTIR (Fourier Transform Infrared) absorption spectroscopy, often applied in the exhaust line, can be used for depletion measurements. Depletion measurements are useful to estimate the efficiency of the plasma for radical production. Absorption measurements are also particularly useful for determining the plasma composition. Other plasma diagnostics such as mass spectrometry of neutral, positive and negative ions, various types of electrical probes and active and passive laser diagnostics or Mie scattering for detecting particles within the plasmas are mostly used only in the research and development phase or in collaboration with academia. Since the diagnostics are difficult to implant on industrial devices, academic research is necessary to improve the understanding of the plasma process, to control the plasma process and to conduct further process development for industry.

Recent advances in the understanding of Electrical Discharge Machining (EDM) show that modern diagnostics lead to advances also in industrial plasmas. In the case of EDM, fast time-resolved emission spectroscopy gives a first insight into the evolution of the plasma parameters during a single spark event. Emission spectroscopy shows the plasma composition, and relative line intensity ratios are useful for measuring the electron temperature within the small discharge [21]. Stark broadening, in particular of hydrogen lines, can be used to determine the electron density, which in the case of the EDM discharge is between 10^{16} to 10^{17} cm^{-3}. The Coulomb coupling coefficient can be calculated from these measurements, which astonishingly shows that the EDM spark is a weakly coupled plasma. Further diagnostics of this weakly coupled plasma is a future challenge. The investigations on the EDM plasma also give rise to new issues, which might be of broad interest [22,23]. One of these issues is the breakdown in liquids. As has been shown, the electrical breakdown in water behaves differently from oil giving rise to new fundamental investigations. Breakdown in liquids is an important topic for the application of plasmas in biology and medicine. Breakdown but also abrasion of electrodes are still topics since the increased power consumption in vehicles demands higher supply voltages leading to redesign of part of the existing electrical equipment such as electrical relays in future.

Recently very important advances have been made in the numerical simulation of applied and industrial plasmas. Without any doubt such theoretical efforts lead to quite substantial advances in

plasma physics and chemistry and also to more efficient and economic industrial plasmas. Significant efforts in the development of simplifications of software for calculation and numerical simulation have been made. In particular, finite element calculations have been very much simplified by a wide choice of algorithms and solvers offered by many commercial software programs. This progress reduces the problems involved with numerical simulation programming, but does not solve the overall and often underestimated complexity of the numerical simulation of plasmas. The inherent multi-scale and the multi-timescale problems in plasmas are still to be overcome in the calculation of plasmas. Also, useful insight from simple models can still be obtained [24] by judicious choice of the relevant physical phenomena which are well adapted to the real situation, without blindly using the full program complexity, thus avoiding long calculation times and large computer memories.

However, it has to be mentioned that not only simulation of the processing plasmas are important, but also many technical aspects of the design of the plasma reactor. In fact, many problems related to the desired outcome of the product are linked to a correct design of the plasma reactor. Heat conduction problems, fluid problems for gas supply and many others have to be solved in order to obtain an efficient, reproducible plasma reactor.

5. Future plasmas for industrial applications

A great industrial potential in future lies in atmospheric plasmas. New and less known applications such as use in biology and medicine but also in technological applications, such as aerodynamics, combustion and ignition, need atmospheric plasmas. The development of the technology and control of atmospheric plasma is an important future field of development and research in industry and academia. In particular, the well-known heating of neutrals observed in many high density plasmas has to be understood and controlled for applications in deposition, functionalization and many other fields.

New materials or advanced material processing and applications have to be explored for plasma treatment and the plasma processing itself must be made more reliable and faster. At present, new applications such as various topics in medicine have found increasing interest in the industrial plasma community. One example is the promising application of fast high power pulsed magnetron sources (HPPMS) for hard material processing, whereas nanosecond pulsed atmospheric discharges find application in advanced combustion, ignition and eventually in aerodynamics.

High rate plasma processing is expected by the use of the modular resonant network antenna. Recent design studies of resonant RF network antennas show that closed (birdcage) and open (planar) configurations of the antenna can be used for plasma production [25,26]. Both are composed of similar electrical meshes as shown in Fig. 4. It has been shown that it is possible to construct complex RF antennas out of the basic network element which can be adapted to their application and which are therefore very user friendly. Resonant modes arise for both closed and open antennas. Each mode is characterized by a resonance frequency determined by the L and C components and the mutual inductances, and has specific current and voltage distributions in the antenna legs [25]. When driven at one of its resonant frequencies, very high currents are generated within the antenna structure. A resonant RF network antenna can therefore be used as a source for inductively-coupled plasma (ICP). There are a large number of different RF antenna arrangements possible in view of geometry and also in view of the RF operation and of the plasma obtained.

Resonant network antennas can be upscaled to run as large area or large volume plasma sources [26] with much fewer difficulties than for the commonly used capacitive and inductive plasma sources. They can be adapted to the size and geometry of the optimal plasma volume for processing. At a resonance frequency, the antenna presents a real input impedance, thus facilitating matching to RF power generators. They show many advantages compared to the conventional capacitively- or inductively-coupled plasma devices and could therefore replace these plasma reactors for certain industrial applications.

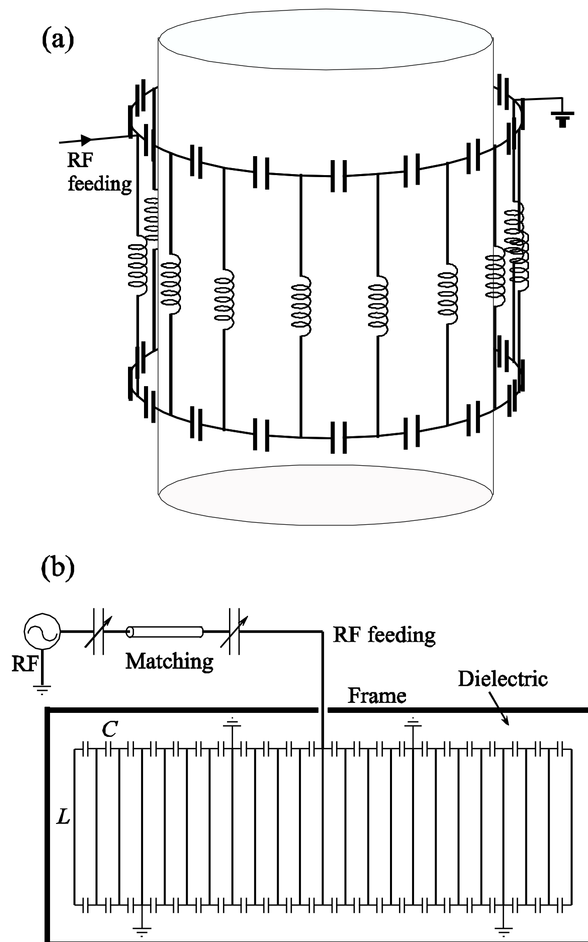

Fig.4 (a) Schematic of a birdcage RF antenna, showing the equivalent electrical circuit, and (b) schematic of a planar RF antenna showing the antenna bars (inductance *L*), the capacitors (*C*), and the matching network.

One of the many promising applications is as a plasma source in future neutral beam injectors for fusion research, but they could also be considered as a replacement for the large area capacitive plasma sources for high rate deposition in batch and roll-to-roll processes. Helicon wave excited discharge produced by the resonant network antenna is thought to be an interesting source for future ion thrusters and related devices. Also wave excited large surface and volume plasmas sources will be possible, as demonstrated by preliminary experiments with whistler-wave heated plasmas [27].

An important point for the development of future plasma reactors is a better adapted design and construction. Many of the present day plasma reactors are not designed to have optimized conditions for the plasmas and the desired process. Such topics include electrical installations such as RF, electrical perturbations, gas flow and gas supply of the plasma, and mechanical construction to inhibit arcing and parasitic discharges. All such matters have to be taken into consideration for a successful, reproducible application of plasmas in industry.

6. Conclusion

In the past, plasma processes in industry have been very successful in opening the way for semiconductors and other related technologies. Also at present, plasma technology plays an important role in producing many daily and high technology products. In future, larger, flexible and improved performance high-density plasmas sources will be demanded. A far better knowledge of the underlying plasma and processes will trigger new impulses in advanced plasma source development including processing of new materials. A strong interaction of research in industry and in academia

can lead to the development of new topics in plasma physics and give rise to innovative plasma processing involving advanced materials.
Industrial plasmas are an important source for new fundamental topics in thermal and non-thermal plasma physics. New developments might lead to new types of processing and to original applications of plasma in modern technologies.

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