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Editorial

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Microplasmas: scientific challenges & technological opportunities

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The plasma state is often referred to as the 4th state of matter. A plasma is characterized by the presence of positive (and sometimes also negative) ions and negatively charged electrons in a neutral background gas. Most of the matter in the visible universe is in the plasma state. Examples include the sun and other stars, interstellar matter, cometary and planetary atmospheres as well as the terrestrial ionosphere. Naturally occurring plasmas on earth are rare and include lightning, polar lights and flames. Plasmas are generated often for technological applications, which include welding arcs, plasma torches, high pressure and fluorescent lamps, the ignition spark in an internal combustion engine, and the vast range of low-pressure plasmas employed in the fabrication of microelectronic devices. Magnetically confined plasmas in nuclear fusion reactors are one of several choices to achieve the extreme conditions under which controlled nuclear fusion might occur in the laboratory. Plasmas are created by supplying energy to a volume containing a neutral gas, so that a certain fraction of free electrons and ions are generated from the neutral constituents. In technical plasma devices, the plasma is generally generated in electrical discharges and the input energy is supplied in the form of electrical energy.

Plasmas can be categorized as either "thermal (or hot) plasmas" or "non-thermal (or cold) plasmas". The main constituents (ions, electrons, neutrals) of a thermal plasma are in thermodynamic equilibrium and can be characterized by a single temperature. This temperature can vary from a few thousand Kelvin for a plasma torch to more than a million Kelvin in fusion plasma devices and in the interior of stars. In a non-thermal plasma, the electron temperature is much higher (10 000 K to more than 100 000 K) than the temperature of the ions and neutrals, which are roughly the same and range from room temperature (300 K) to about 2500 K. We note that the concept of a thermodynamic temperature requires that the energy distribution of the particles in question can be described by a Maxwell-Boltzmann distribution function corresponding to a single temperature. This is usually not the case for the electrons in a non-thermal plasma, whose energy distribution function is typically highly non-Maxwellian. Nevertheless, the nomenclature "electron temperature" is also commonly used for the mean energy of the electrons in these cases.

Faraday was the first to realize that an ionized gas has unique properties [1–3] and introduced the concept of ions as carriers of electricity and distinguished between cathode and anode and he even distinguished between cations (moving to the cathode) and anions (passing to the anode). The term plasma was coined much later by Langmuir and Tonks [4,5]. The work of Wilson [6] and Townsend [7,8] in the early 20th century established that conductivity in discharges was due to ionization of atoms or molecules by electron collisions and subsequent drift along the electric field. It was obvious early on that cold glow discharge plasmas had properties that were very different from those of hot arc discharges. For a long time it was believed that non-thermal plasmas could exist only at low pressure and were the only plasmas that could be generated in large volumes. We now know that non-thermal plasmas can also be generated at high pressure (incl. atmospheric pressure), albeit not easily in large volumes. The properties of non-equilibrium plasmas are discussed in many books and publications (see e.g. [9–12] and references therein), to which we refer the interested reader for further details.

High-pressure plasmas represent an environment where collisions and radiative processes are dominated by (i) step-wise processes, i.e. the excitation of states

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followed by collisions of the excited species with other particles resulting in new energy transfer routes and by (ii) three-body collisions leading e.g., to the formation of excimers. The dominance of collisional and radiative processes beyond binary collisions involving ground-state species allows for many applications of high-pressure plasmas such as high power lasers, opening switches, novel plasma processing applications, electromagnetic absorbers and reflectors, remediation of gaseous pollutants, medical sterilization and biological decontamination, as well as excimer lamps and other non-coherent vacuum-ultraviolet (VUV) light sources [13]. However, self-sustained diffuse plasmas tend to be unstable at high pressure due to their susceptibility to filamentation and the transition to an arc (see [9–12,14]), which limits their practical utility. A promising approach to generate and maintain stable high-pressure plasmas is based on the recognition that plasmas confined to critical dimensions below about 1 mm, so-called "microplasmas", display a remarkable stability preventing arcing. There are several factors that contribute to the stabilization of microplasmas, not all of them fully understood at this point in time. One stabilizing factor can be explained in terms of "*pd* scaling". The voltage required to ignite a discharge, the so-called breakdown voltage, depends on the product of gas pressure "*p*" and electrode separation "*d*". If one increases the pressure for a fixed value of "*d*", the required breakdown voltage increases. At atmospheric pressure (and electrode separations of centimeters to tens of centimeters, which are typical for low-pressure plasmas), breakdown voltages are in the kV range. The high breakdown voltage leads to a high current density after the discharge is ignited, particularly in the cathode fall of the discharge. The high current density is the source of discharge instabilities in the cathode fall region, which quickly lead to the formation of an undesirable arc. As a consequence of "*pd* scaling", the breakdown voltage can be kept low, if the electrode separation "*d*" is reduced when the pressure "*p*" is increased. At atmospheric pressure, d-values below 1 mm are required to keep breakdown voltages sufficiently low to avoid the glow-to-arc transition after plasma ignition. Another factor that at least in part contributes to the stability of high-pressure microplasmas are the high losses of charge carriers to the surrounding walls. The typical operating parameters of microplasmas (pressures up to and exceeding 1 atm (760 torr) and dimensions below 1 mm) correspond to "*pd*" values of between 1 and 10 torr cm. These "*pd*" values are similar to those for large-volume, low-pressure plasmas. However, the current and the energy densities in microplasmas are much higher.

Microdischarges generated in spatially confined cavities began to appear in the literature in the mid-1990s. Schoenbach et al. [15] were the first to report the stable atmospheric-pressure operation of a microdischarge in a cylindrical hollow cathode geometry and coined the term "microhollow cathode discharge (MHCD)" for this type of microdischarge. The phrase "hollow cathode" historically refers to a specific mode of discharge operation, in which the sustaining voltage drops as the current increases, i.e. the discharge has a "negative differential resistance" (hollow cathode or subnormal negative glow mode). Nowadays, MHCDs are often not operated in the hollow cathode mode, but as normal or abnormal glow discharges. Therefore, the inclusion of the phrase 'hollow cathode' in the name MHCD might be misleading. As a consequence, other groups have been referring to these discharges simply as "Microdischarges" [16,17] or "microstructured electrode arrays" [18]. In an effort to avoid blurring the distinction between discharge device geometry or structure and its operational characteristics, the phrase "microhollow cathode discharge, MHCD" has largely been replaced by the terms "microplasma", "microcavity plasma", or "microdischarge" [19]. Applications of microdischarges often require the use of two-dimensional arrays of individual microdischarges, either operated in parallel or in series, or both. Microdischarges can be operated in parallel without individual ballast resistors, if the discharges are operated in the range where the current-voltage (I-V) curve has a positive slope [15,18,20,21]. In regions where the I-V characteristics has a negative slope (hollow cathode mode or subnormal glow mode) or is flat (normal glow mode), arrays can be generated by using a distributed resistive ballast such as semi-insulating silicon as anode material [22] or multilayer ceramic structures where each microdischarge is individually ballasted [23,24].

Frequently used microplasma sources include the capillary plasma electrode (CPE) discharge, which employs dielectric capillaries that cover one or both electrodes of a discharge device [25–27]. The CPE discharge exhibits a mode of operation, where the capillaries serve as plasma sources and produce jets of high-intensity plasma at high pressure, which emerge from the end of the capillary and form a "plasma electrode". A variety of microplasma sources were developed for chemical analysis purposes leveraging rapid advances in microfabrication techniques [28]. This allowed the miniaturization of known plasma concepts and their integration into "lab-on-a chip" analytical tools such as plasma atomic spectrometry, plasma mass spectrometry, and plasma gas and liquid chromatography. Miniature inductively and capacitively coupled plasmas, often generated in capillary tubes, are among the most widely used plasma sources used for chemical analysis. Other concepts such as microwave plasmas, microdischarges in hollow cathode geometries and microstructure electrode (MSE) discharges have also been utilized [29]. Several atmospheric-pressure plasma jets at the microscale (micro-APPJs) have been developed by various groups and are widely used in applications ranging from thin film deposition to sterilization and biological decontamination to biomedical, medical, and dental applications and the treatment of temperature-sensitive substrates [30].

Variants of the original microhollow cathode design have been used [19,28,31–33] such as parallel plates, arbitrarily shaped holes in a solid cathode, slits in the cathode, spirals, micro-tubes with the anode at the orifice, or inserted through the walls, and micro-slots. Common to all these geometries are the dimensions of the cathode hollows which are on the order of hundred microns. A microdischarge, whose characteristic plasma dimensions are near the upper end of the 1 mm size scale, is a variant of the well-known dielectric barrier discharge (DBD) [34], the so-called cylindrical dielectric barrier discharge [35–39], C-DBD. This discharge source consists of a thin and thin-walled dielectric tube, with two straps of Cu wrapped around it, which serve as the two electrodes. A stable, high-frequency discharge plasma can be generated inside the tube in the space between the electrodes.

While dedicated sessions devoted to the science and application of microplasmas are nowadays part of many plasma and gas discharge conferences, the most prominent forum where microplasma research is presented in discussion is a dedicated workshop series, the international workshop on microplasmas (IWM). The origin of this workshop series dates back to 2003 when a workshop was held in Japan entitled "the new world of microplasmas", which, for the first time, devoted an entire conference to the exciting new scientific challenges and emerging technological opportunities for microplasmas and microdischarges. Less than two years later, "the second international workshop on microplasmas (IWM-2004)" in the USA marked the beginning of the IWM workshop series, with workshops now being held about every 2 years. The 6th workshop will take place in Paris, France in the spring of 2011. The establishment of this series of workshops reflects the continuing advances in the science and technology of microplasmas. The present topical issue devoted to "microplasmas: scientific challenges and technological opportunities" contains a selection of papers, whose main emphasis is (1) on advancing our basic scientific understanding of microplasmas or (2) on applications of microplasmas, where insight into the underlying basic plasma science is also provided.

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