THE PLASMA CONNECTION

IEEE NPSS NUCLEAR & PLASMA SCIENCES SOCIETY

FROM THE IEEE NUCLEAR & PLASMA SCIENCES SOCIETY APRIL 2022

Microplasmas: A Platform Technology for Plasma Applications

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Microplasmas are commonly defined as plasmas with at least one dimension in the submillimeter range. Although first introduced a few decades ago, interest and activities in basic microplasma research as well as in the use of such microplasma for a variety of applications has increased significantly only in the last 20 years. Some microplasmas are thermal or "hot", that is the gas temperature and the electron temperature are roughly the same and are far above room temperature and can reach thousands of degrees K. Another group of microplasmas is nonthermal or "cold", with gas temperatures much below the electron temperature. A significant fraction of the electrons in a nonthermal plasma have sufficient energy to create high excitation, ionization, and dissociation rates of the atomic and molecular constituents

Fig. 1: Radially outward directed microplasmas used for the decontamination of the inside of a tube.

of the plasma. Research into nonthermal microplasmas has enjoyed an enormous growth in the past two decades [1]. These plasmas are particularly attractive for a plethora of applications [2] because they can be operated stably at high gas pressures, in rare gases as well as in molecular gases and gas mixtures and can be sustained in a direct current (dc) mode as well as in pulsed dc and in alternate current (ac) modes. Modeling and improved diagnostics have allowed us in the past decade to gain more insight into the specific properties of nonthermal microplasmas. Electron densities exceeding 10^{16} cm^{-3} have been measured in pulsed microplasmas [1]. Gas temperatures, on the other hand, can be close to room temperature at low currents in rare gases and generally reach not more than 2000 K in atmospheric-pressure air microplasmas. With discharge voltages of a few hundred volts and current densities of the order of 10 A/cm^2 (at currents of 1 mA in a microplasma device with a 100 μm cathode opening), the power densities in such a microplasma with typical dimensions of 100 μm can reach values on the order of 10^5 W/cm^3 [1].

The nonthermal nature of microplasmas in conjunction with the possibility of stable high-pressure operation, high power density, electron energy distributions with a significant number of energetic electrons, low gas temperatures (down to ambient temperature), and the possibility to build two-dimensional arrays without individual ballasting made it possible to create microplasma devices for a wide range of applications. The development of excimer lamps with emissions in the vacuum ultraviolet (VUV) was one of the first application-oriented developments using microplasmas [3]. The same basic mechanism, three-body reactions (that is reactions/collisions involving 3 atoms/molecules), forms the basis for microplasma-based ozone generators [4].

The resistive character of microplasmas under certain operating conditions giving rise to the creation of large microplasma arrays allowed the fabrication of flat panel light sources with more than 10^5 individual microplasmas. Addressable flat panels have also been developed based on the same fabrication method. Another area where microplasmas have been successfully introduced is in material processing, particularly the synthesis of nanoparticles [5,6].

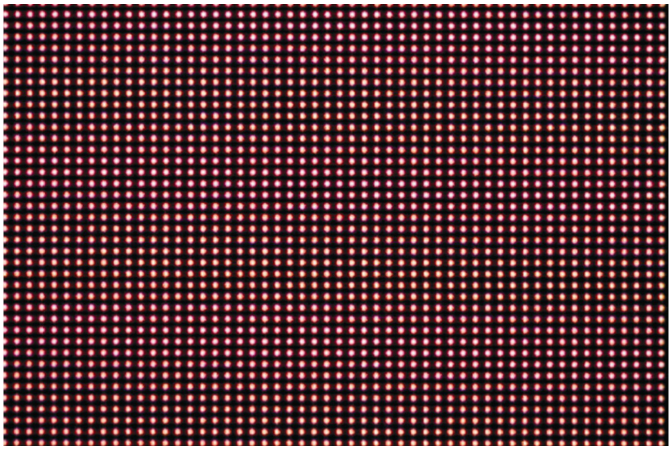

Fig. 2: A 500 x 500 array of microplasmas.

Plasma medicine is an emerging area of application, which has gained strongly in interest by the scientific community. Major advances were made possible by the development of plasma sources that are biocompatible (i.e. satisfy strict conditions in terms of their electrical, chemical, and thermal properties), consist of biocompatible materials, can generate copious amounts of reactive radicals and deliver them to biological tissue via plasma jets. We note that medical applications of plasmas also bear risks, which should be properly assessed [7]. Besides medical applications, studies on environmental applications have been performed (see e.g. Becker [8] and references therein). Lesser known, but important applications of microplasmas, are in the area of detectors [8] and even microthrusters [9].

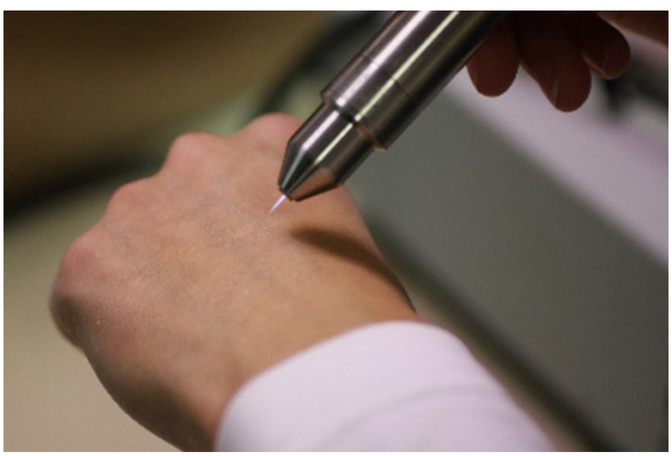

Fig. 3: Atmospheric-pressure plasma jet interacting with human skin.

It should perhaps be noted that the rapid development of microplasma applications has often occurred by trial-and-error without having a good understanding of the underlying basic science. Plasma applications as diverse as surface modification and functionalization, light sources, ozone generation, pollution control, biological inactivation, sensors rely on the plasma-initiated generation of chemically reactive species, in particular reactive oxygen and nitrogen species. We only have an understanding of some of the key plasma chemical reaction pathways that drive the process in a few applications. Moreover, in almost all areas of application there is a lack a detailed knowledge of the coupling of the plasma physics to the plasma chemistry. Researchers do not yet have the level of understanding of the basic plasma physics that will allow precise tailoring of the plasma parameters such as plasma composition and gas temperature, power density, electron density, and electron energy distribution to selectively maximize the generation of certain plasma species, while minimizing or suppressing the formation of others. Thus, there is a lack of ability to achieve full control of the plasma chemistry in many applications by making use of insight into the basic plasma physics.

That said, applications can also be powerful drivers and motivators for basic science and the development of new plasma sources. As an example, demands for plasma sources with very application–specific operating parameters and performance characteristics led to the development of a wide range of microplasma sources [1] starting with the original concepts of a microplasma generated between parallel-plate electrodes that included dc microplasmas between a flat cathode and a ring-shaped electrode (so-called cathode boundary layer plasmas), and ac (microwave) microdischarges between parallel edge electrodes. Very quickly, the need arose for generating and sustaining microplasmas in two-dimensional microcavity electrode structures excited by dc, ac, and pulsed power. By now, various microplasma arrays are being used with arrangements where the individual microplasma are operated in series or in parallel.

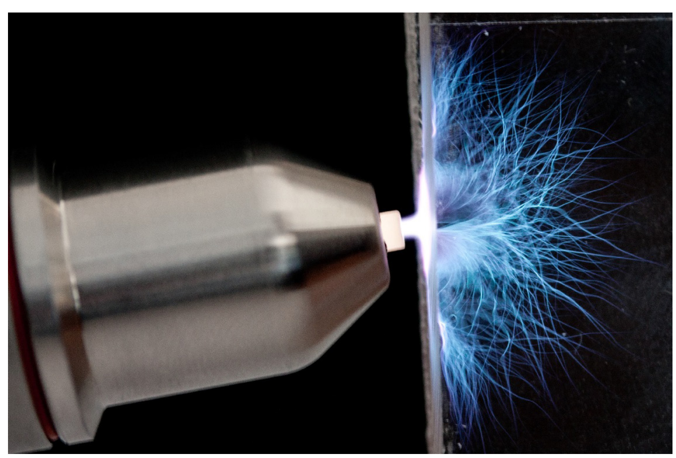

Fig. 4: Atmospheric-pressure plasma jet generating microplasmas on the opposite side of a surface.

The need for plasma treatment of objects, whose size and shape did not allow them to be placed in the microplasma gaps for direct place treatment but rather required remote plasma treatment, led to the advent of various types of atmospheric-pressure plasma jets (APPJs) [10]. APPJs have gained wide spread use in the past 10 years. In the rapidly developing field of plasma medicine, the excitement stemming from successful applications such as seeing how the use of a microplasma can accelerate blood coagulation or stimulate wound healing has triggered many studies into identifying the underlying chemical and biological reaction pathways initiated by the plasma.

Text and images by K. Becker; Edited by M. Laroussi

The Plasma Connection is a publication of the IEEE Nuclear and Plasma Sciences Society.

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