Lecture22: Atmospheric Plasma

Plasma Physics 1

APPH E6101x

Columbia University

Fall, 2015

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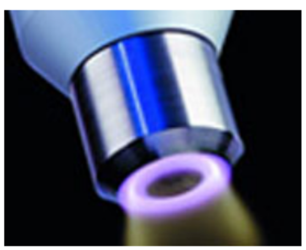

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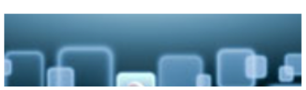

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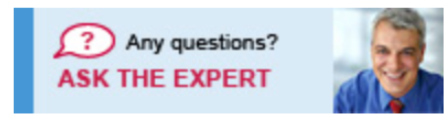

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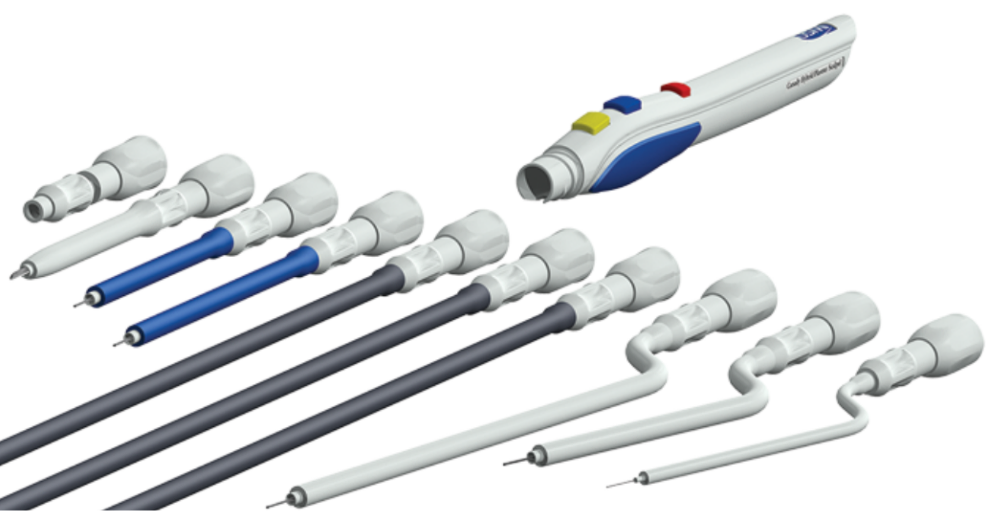

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PHYSICS OF PLASMAS **22**, 121901 (2015)

Preface to Special Topic: Plasmas for Medical Applications

Michael Keidar[1,a)] and Eric Robert[2]
[1] *Mechanical and Aerospace Engineering, Department of Neurological Surgery, The George Washington University, Washington, DC 20052, USA*
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(Received 30 June 2015; accepted 2 July 2015; published online 28 October 2015)

Intense research effort over last few decades in low-temperature (or cold) atmospheric plasma application in bioengineering led to the foundation of a new scientific field, plasma medicine. Cold atmospheric plasmas (CAP) produce various chemically reactive species including reactive oxygen species (ROS) and reactive nitrogen species (RNS). It has been found that these reactive species play an important role in the interaction of CAP with prokaryotic and eukaryotic cells triggering various signaling pathways in cells. © *2015 AIP Publishing LLC.*
[http://dx.doi.org/10.1063/1.4933406]

PHYSICS OF PLASMAS 22, 121901 (2015)

Preface to Special Topic: Plasmas for Medical Applications

Michael Keidar[1,a)] and Eric Robert[2]
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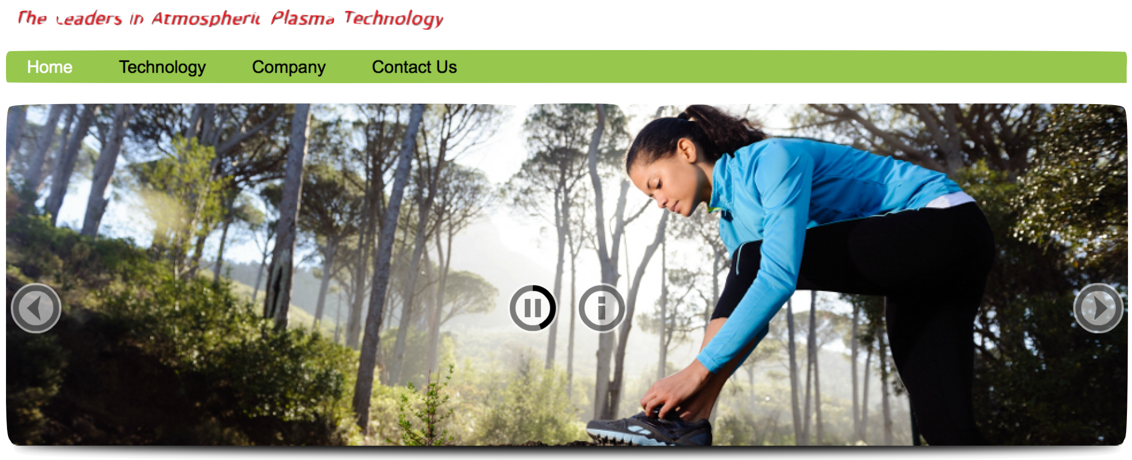
The Atmospheric-Pressure Plasma Jet: A Review and Comparison to Other Plasma Sources

Andreas Schütze, James Y. Jeong, Steven E. Babayan, Jaeyoung Park, Gary S. Selwyn, and Robert F. Hicks

(Invited Paper)



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Dr. Gary S. Selwyn, Ph.D founded APJeT, Inc., in 2002 and serves as its Chief Technology Officer. Dr. Selwyn is the principal founder of APJeT, Inc. and was successful in obtaining APJeT's exclusive license for the patent portfolio from LANL and the necessary investment capital from corporate sponsors. He served as Chairman of the Board at APJeT, Inc., and serves as its Director. When he is not inventing, Dr. Selwyn enjoys scuba diving, skiing, sailing, fishing, fitness activities, hiking, camping, museums, classical music, and opera. Dr. Selwyn has been a pioneer in the field of plasma chemistry and plasma processing of materials for 25 years. He is widely known for his discovery of plasma-generated particulate contamination in chip manufacturing processes

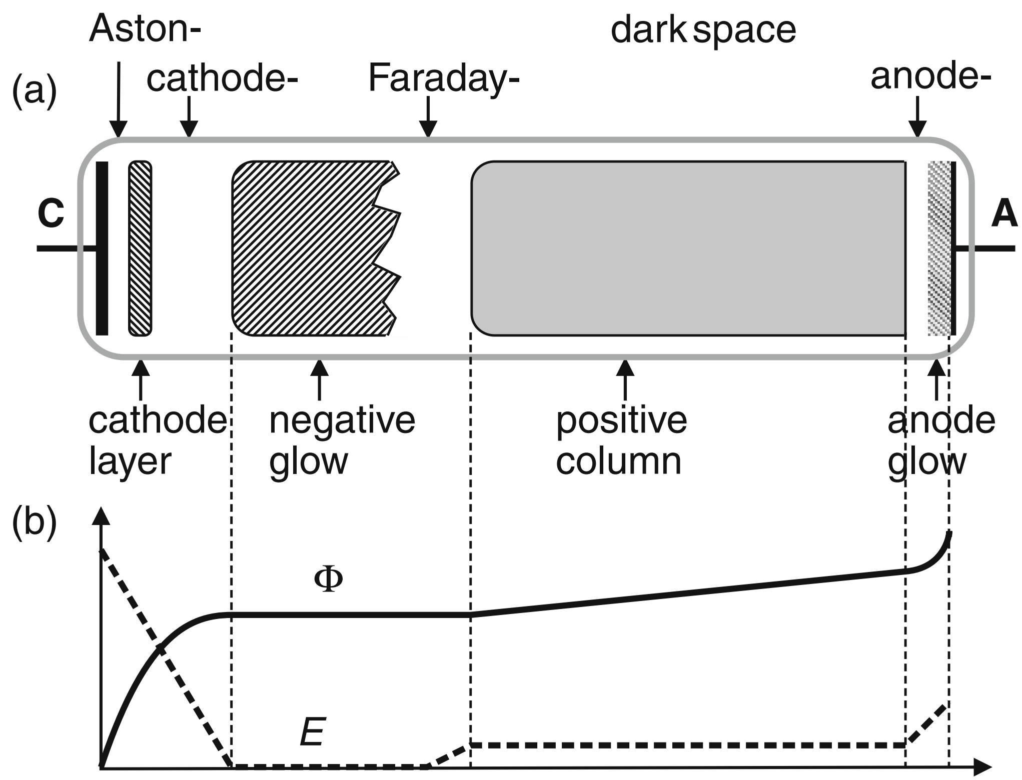


Fig. 11.2 Anatomy of a glow discharge in a long cylindrical tube with plane cathode (C) and anode (A). (**a**) Various dark spaces and luminous regions are indicated. (**b**) Sketch of the electric potential Φ and axial electric field E in the normal glow discharge

The proportionality to p^2 results from $E_0 \propto p$, $d_\mathrm{n} \propto p^{-1}$, and $\mu_\mathrm{i} \propto p^{-1}$. Hence, j/p^2 is a similarity parameter.

[2] Prof. Sanborn C. Brown told the anecdote of the gas-discharge pioneer Wilhelm Hittorf, who attempted to find the maximum length of the positive column [353]. "Week after week his discharge tube grew as he added meter after meter [. . .] His tube went all the way across the room, turned and came back, turned again until his laboratory seemed full of thin glass tubing. It was summer [. . .] and he opened the window to make it bearable. Suddenly from outside came the howl of a pack of dogs in full pursuit and flying through the window came a terrified cat to land [. . .] in the middle of the weeks and weeks of labor. 'Until an unfortunate accident terminated my experiment', Hittorf wrote, 'the positive column appeared to extend without limit.' "

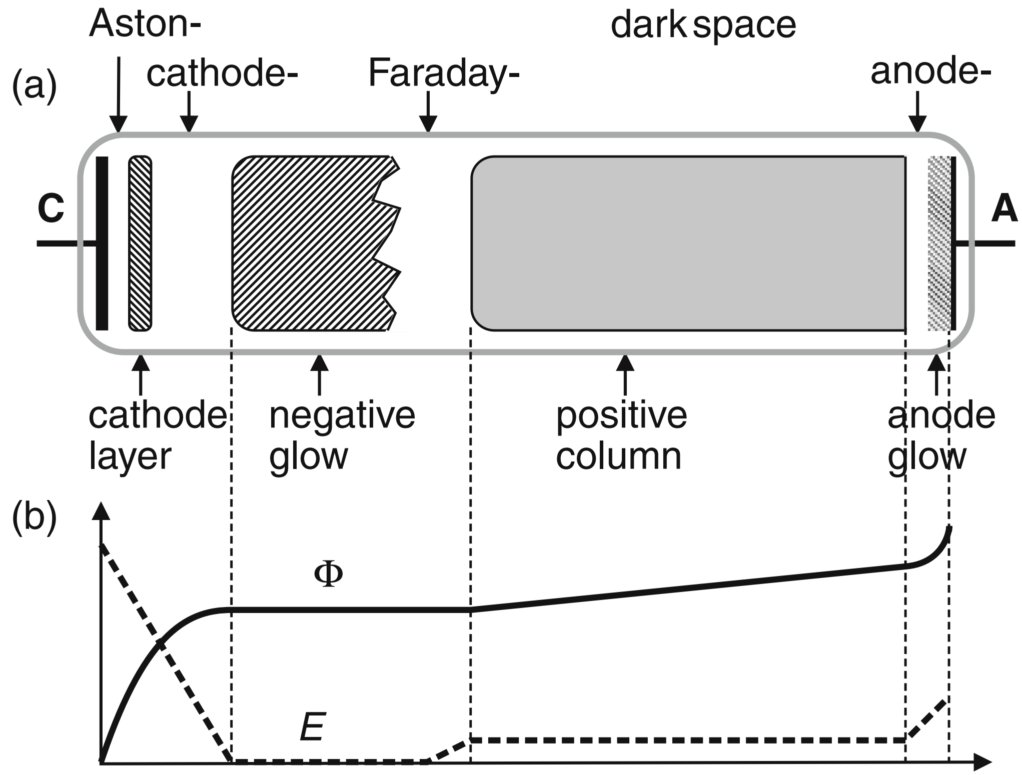


Fig. 11.2 Anatomy of a glow discharge in a long cylindrical tube with plane cathode (C) and anode (A). (**a**) Various dark spaces and luminous regions are indicated. (**b**) Sketch of the electric potential Φ and axial electric field E in the normal glow discharge

The influence of the tube radius a on the discharge is given by the production-loss balance (4.43), $\nu_{\rm ion} = D_{\rm a}\,(2.405/a)^2$. Noticing, that $\nu_{\rm ion} \propto p$ and $D_{\rm a} \propto p^{-1}$, we find that the product of gas pressure and tube radius, $p\,a$, must be a similarity parameter. Similar scalings with $p\,d$ were discussed for the breakdown voltage, the thickness of the normal glow, and the dimensions of the hollow cathode.

Last not least, the $p\,d$ scaling explains, why the diameter of fluorescent tubes could be reduced from $1.5''$ to $1''$, or even to $1/4''$ in compact fluorescent tubes, with a corresponding increase in gas pressure, after phosphor coatings were developed that could withstand the increased heat flux. It is also not surprising, that modern gas discharges at atmospheric pressure are tiny objects of sub-millimeter dimensions.

Abstract—**Atmospheric-pressure plasmas are used in a variety of materials processes. Traditional sources include transferred arcs, plasma torches, corona discharges, and dielectric barrier discharges. In arcs and torches, the electron and neutral temperatures exceed 3000 °C and the densities of charge species range from 10^{16}–10^{19} cm^{-3}. Due to the high gas temperature, these plasmas are used primarily in metallurgy. Corona and dielectric barrier discharges produce nonequilibrium plasmas with gas temperatures between 50–400 °C and densities of charged species typical of weakly ionized gases. However, since these discharges are nonuniform, their use in materials processing is limited. Recently, an atmospheric-pressure plasma jet has been developed, which exhibits many characteristics of a conventional, low-pressure glow discharge. In the jet, the gas temperature ranges from 25–200 °C, charged-particle densities are 10^{11}–10^{12} cm^{-3}, and reactive species are present in high concentrations, i.e., 10–100 ppm. Since this source may be scaled to treat large areas, it could be used in applications which have been restricted to vacuum. In this paper, the physics and chemistry of the plasma jet and other atmospheric-pressure sources are reviewed.**

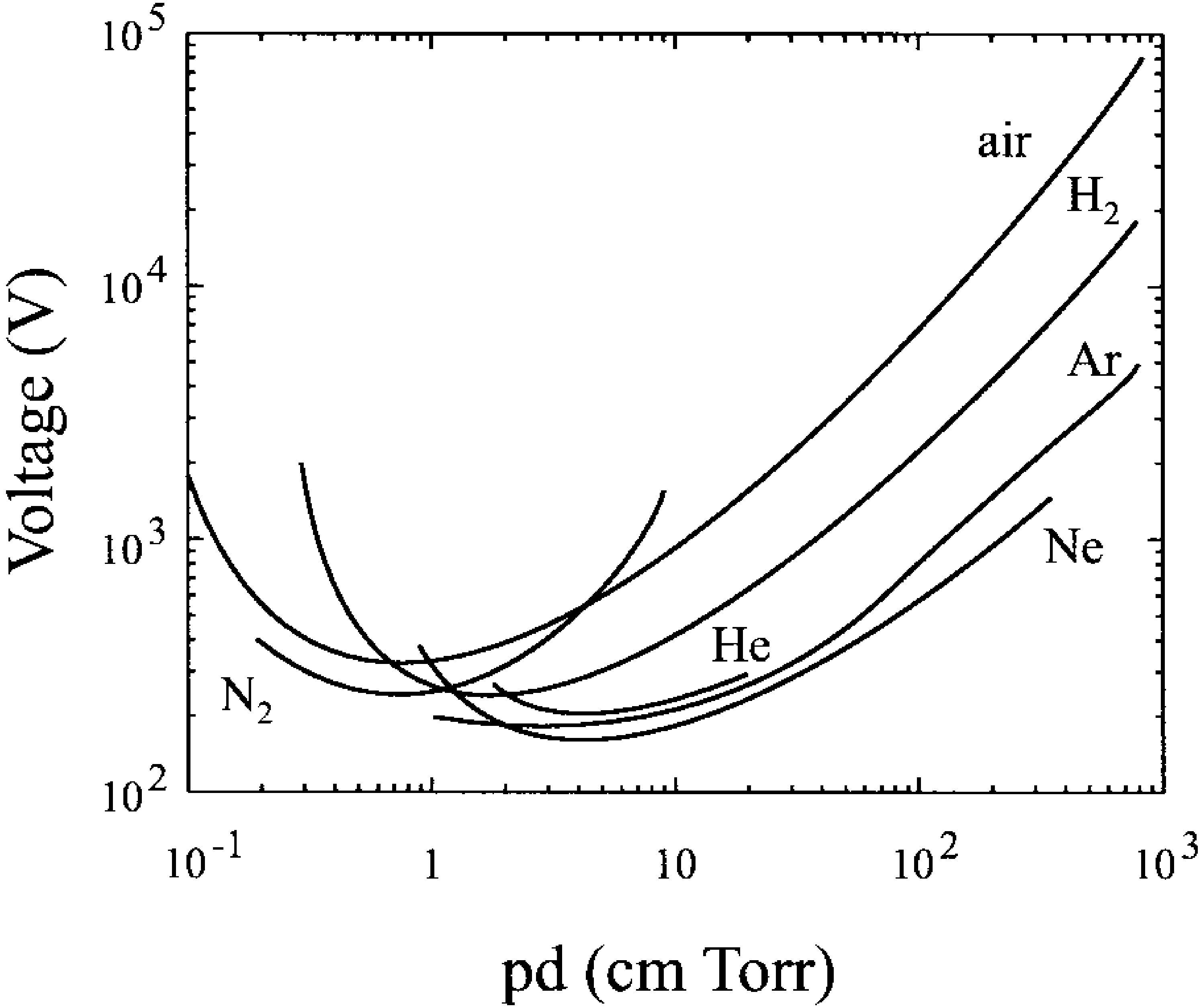


Fig. 1. Breakdown potential in various gases as a function of the pressure and gap distance $p \times d$ for plane-parallel electrodes [8].

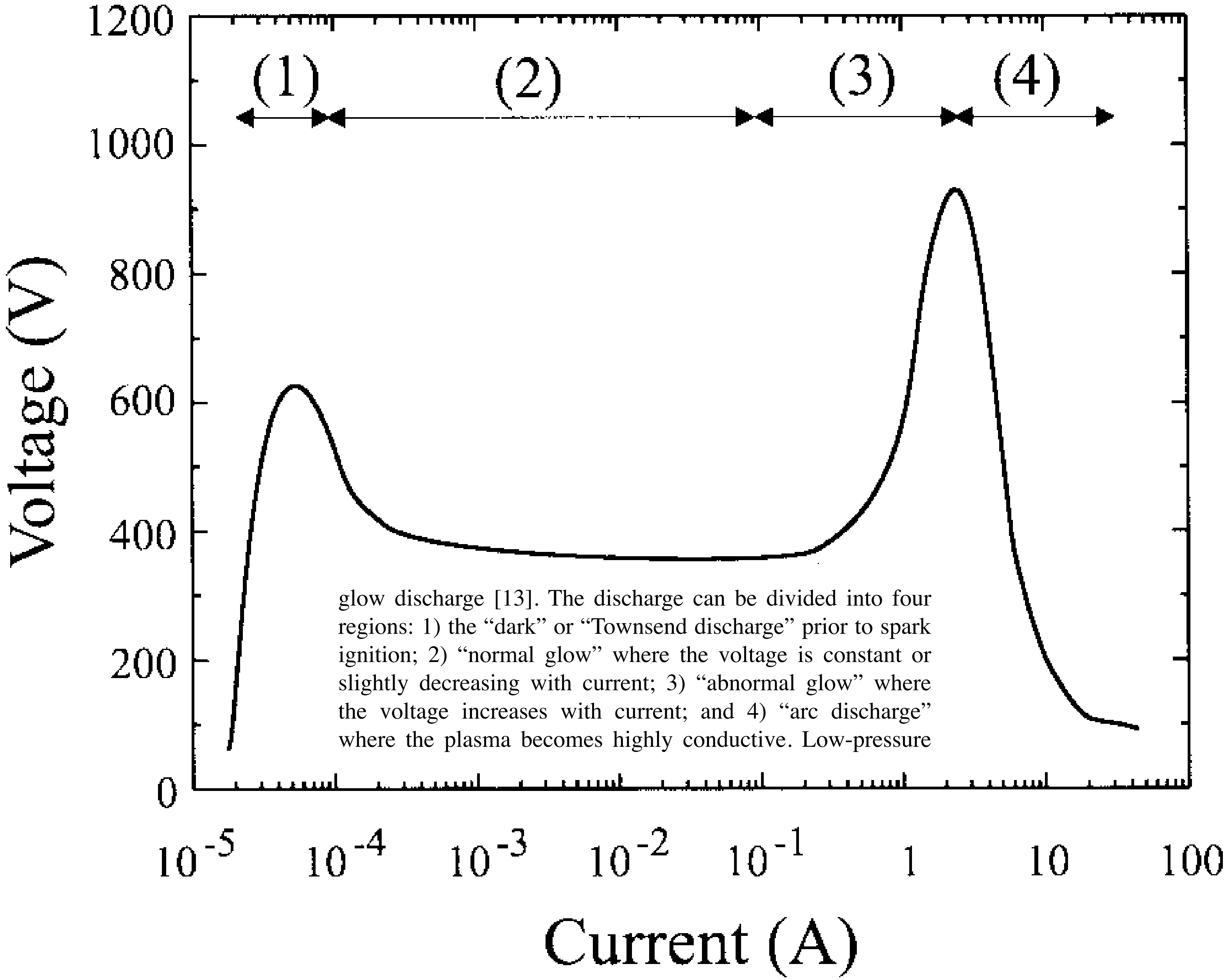


Fig. 2. Current–voltage characteristics of a low-pressure DC glow discharge at 1 torr [13].

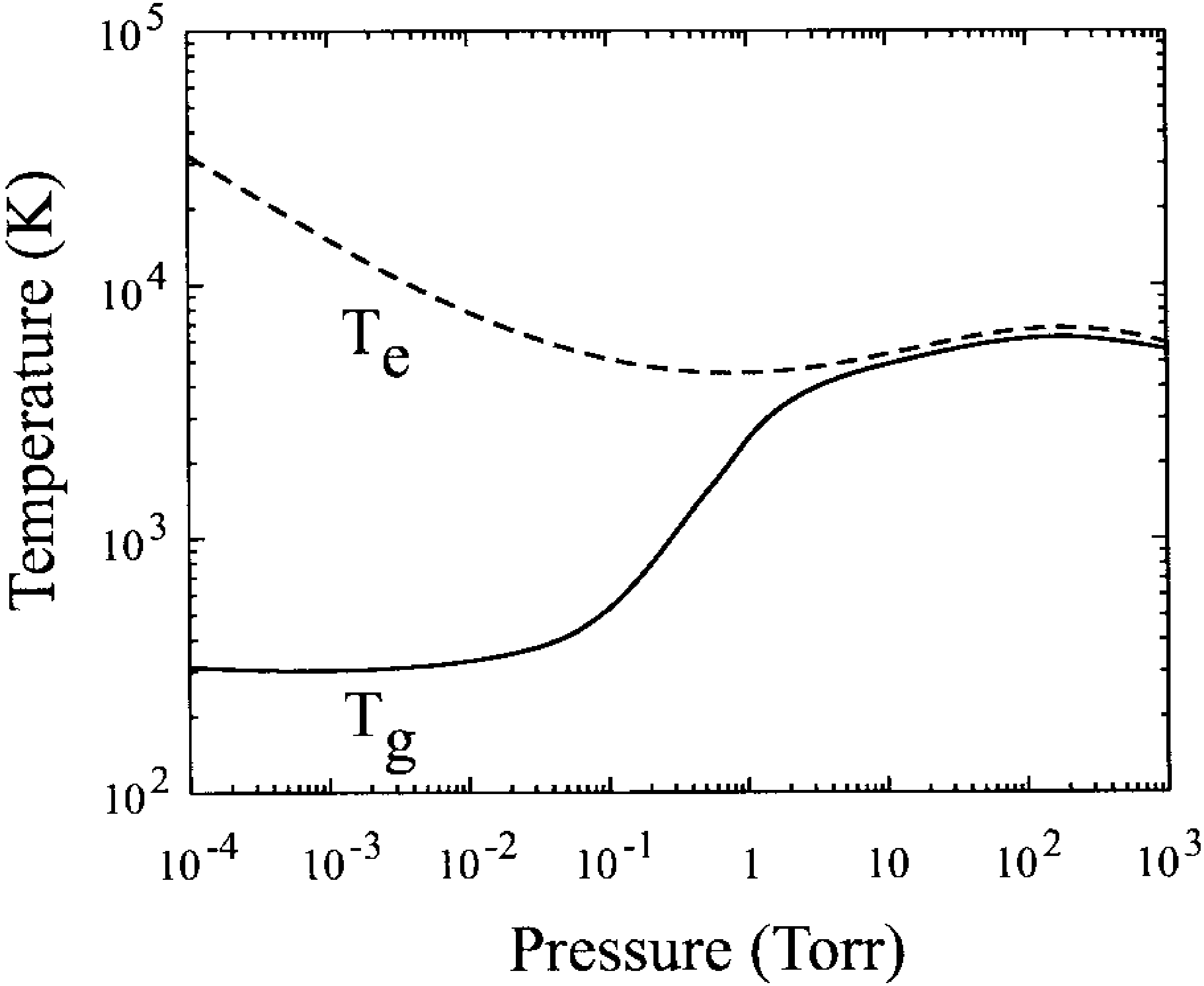


Fig. 3. Schematic of the electron and gas temperature as a function of pressure in a plasma discharge at constant current [14].

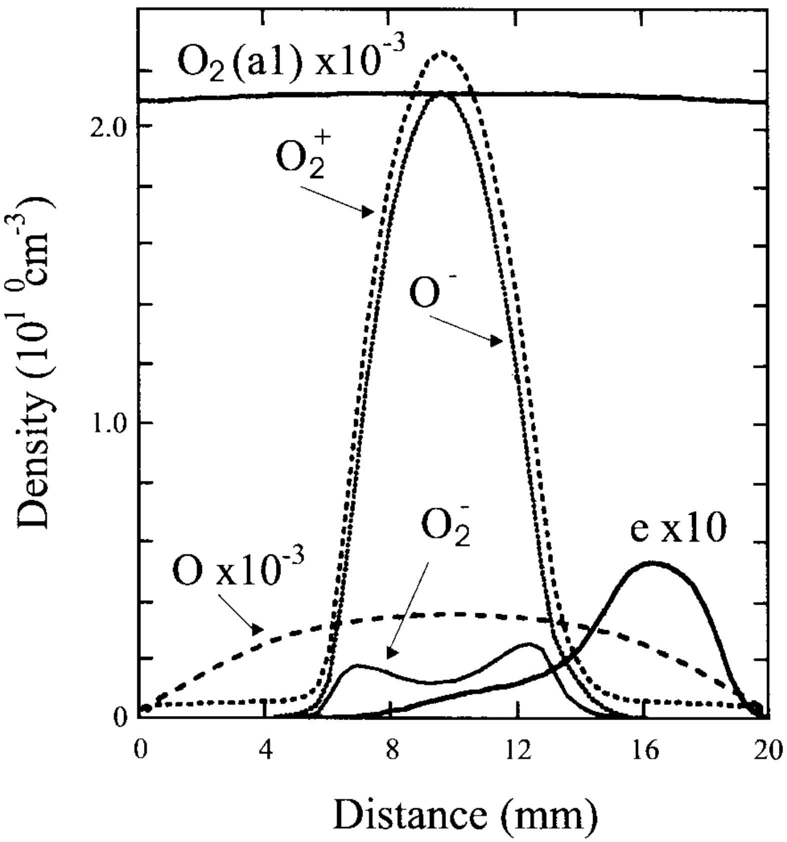


Fig. 4. Spatial particle distributions in a parallel plate O_2 RF discharge at $\omega t = \pi/2$ for $V_{\rm rms} = 200$ V [16].

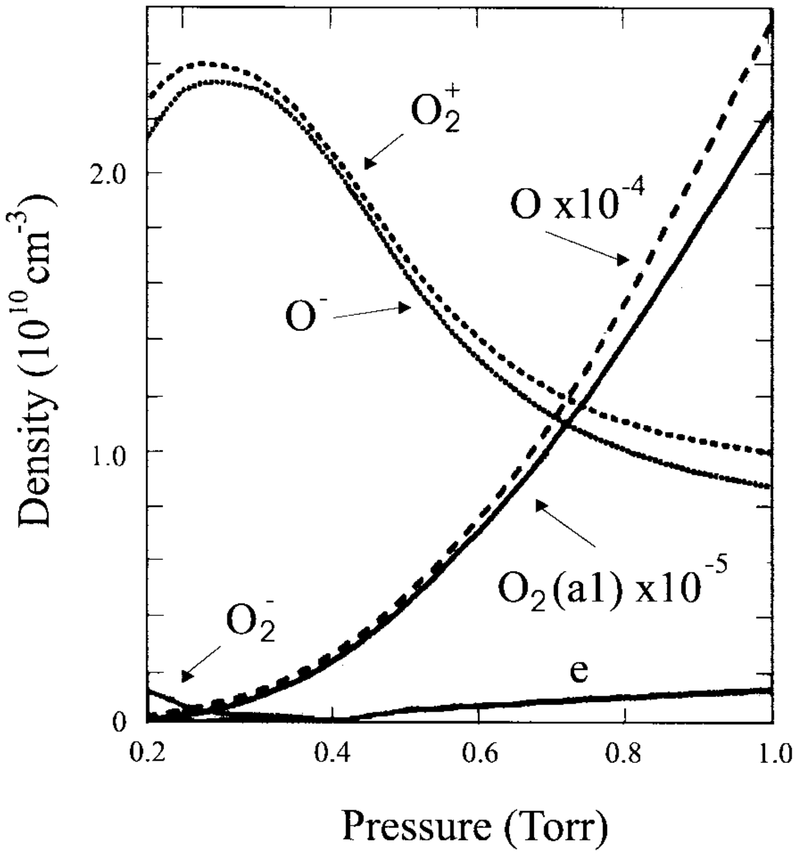


Fig. 5. Time-averaged number densities of each particle in the center of the discharge as a function of pressure in the range between 0.15 and 1 torr [16].

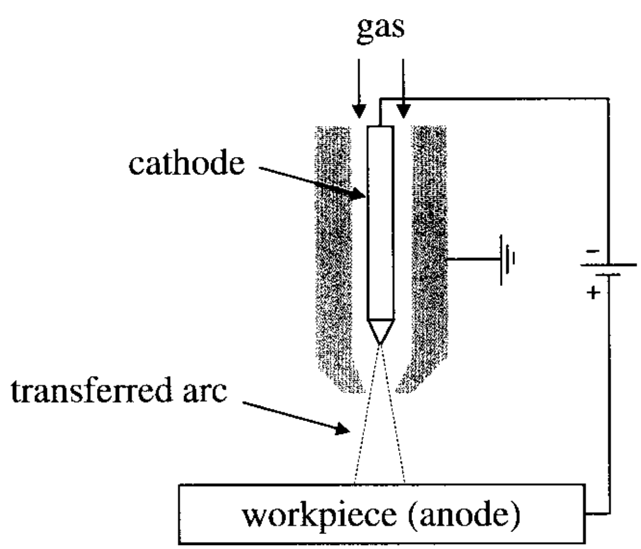


Fig. 6. Schematic of a transferred arc apparatus.

III. Transferred Arcs and Plasma Torches

Transferred arcs are used to cut [3], [4], [19], and [20], melt [4] and [21], and weld condensed materials. A schematic of such a device is shown in Fig. 6. It consists of a cylindrical shaped cathode, an outer grounded and water-cooled shield, and a workpiece as the anode. By feeding argon and hydrogen, oxygen, or air between the cathode and shield, and by applying DC power of up to 200 kW, an arc between the electrodes may be ignited and sustained. Typical operation conditions and properties are 1–15 l/s gas flow, 50–600 A, 10^4 MW/m^2, gas temperatures between 3000 and 20 000K, and a nozzle-to-sample distance of 5–10 mm [19]–[22]. These parameters may vary, depending on the nozzle diameter and materials to be cut. Transferred arcs can slice steel plates up to 150 mm thick. For example, a plate, 40 mm thick, was cut at 0.7 m/min with a 600 A arc [23].

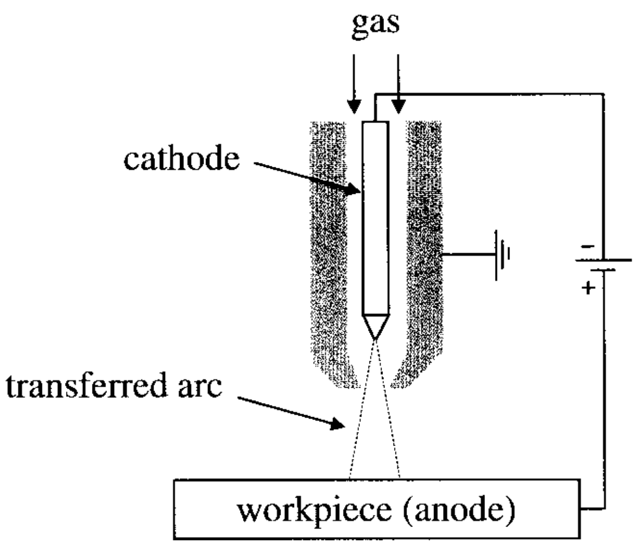


Fig. 6. Schematic of a transferred arc apparatus.

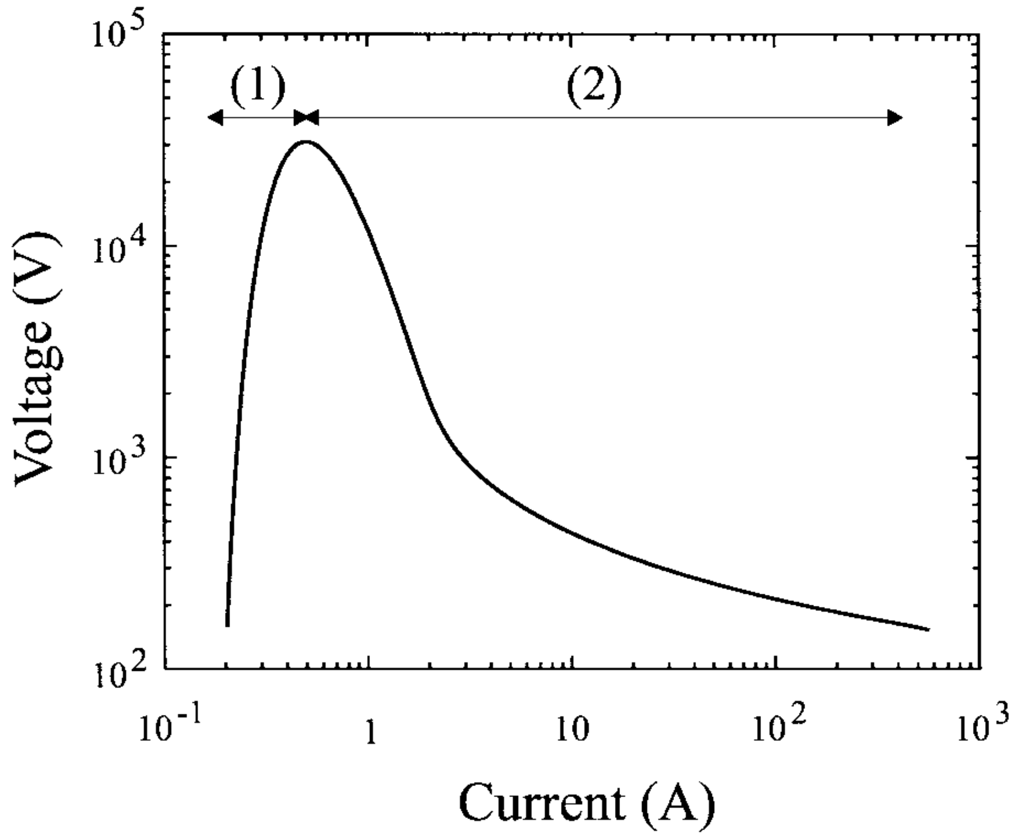


Fig. 7. Current–voltage characteristics of an atmospheric-pressure arc.

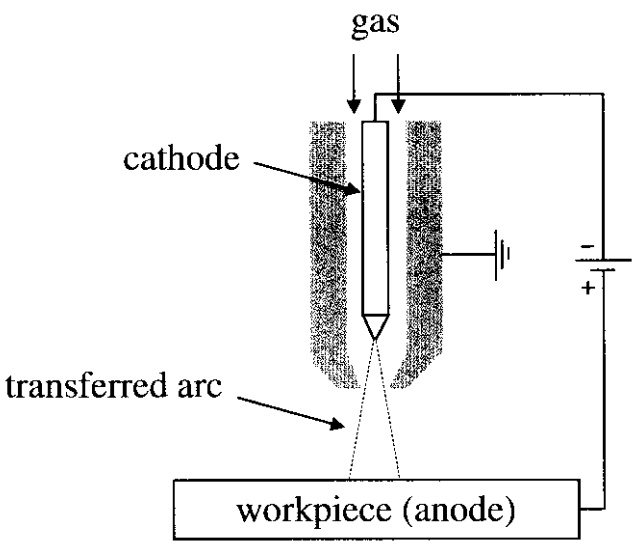


Fig. 6. Schematic of a transferred arc apparatus.

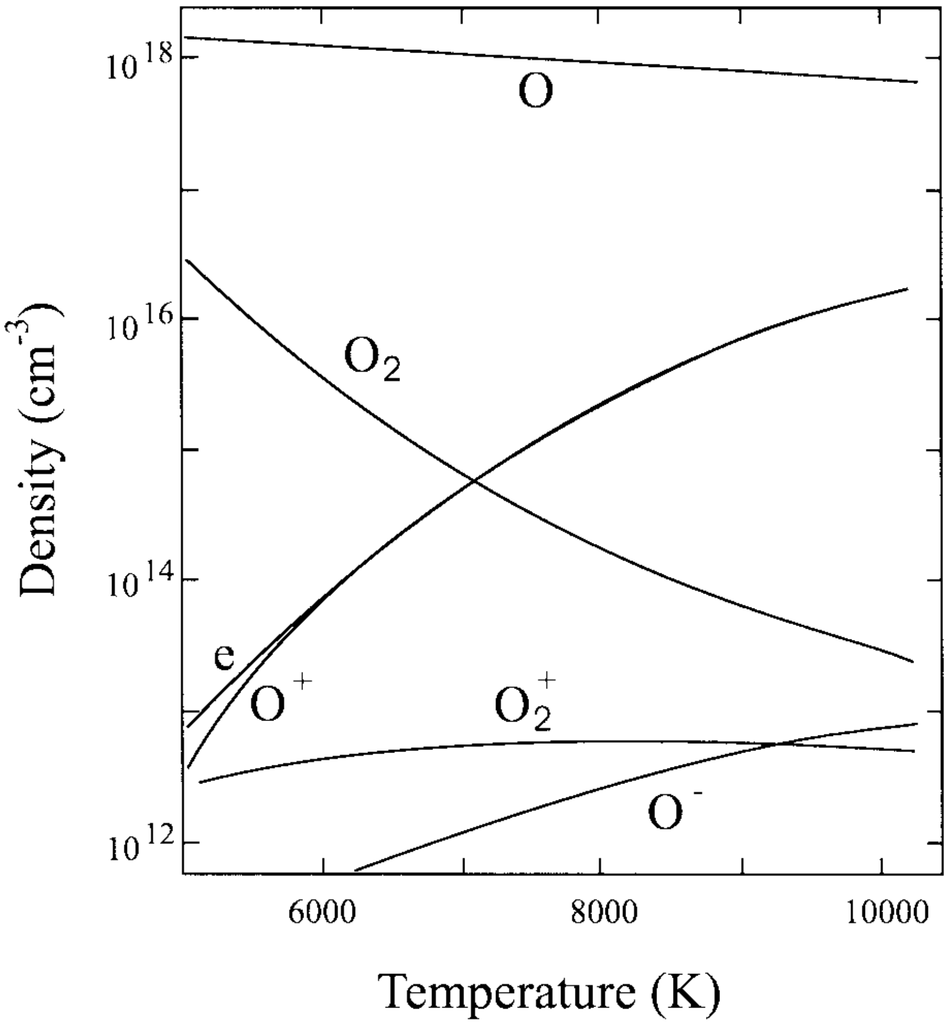


Fig. 8. Composition of an oxygen plasma arc at 0.95 atm as a function of the temperature [42].

IV. Corona Discharge

A corona discharge appears as a luminous glow localized in space around a point tip in a highly nonuniform electric field. The physics of this source is well understood [5], [8], [12], [44]–[47]. The corona may be considered a Townsend discharge or a negative glow discharge depending upon the field and potential distribution [45]. Fig. 9 shows a schematic of a point-to-plane corona. The apparatus consists of a metal tip, with a radius of about 3 μm, and a planar electrode separated from the tip by a distance of 4–16 mm [47]. The

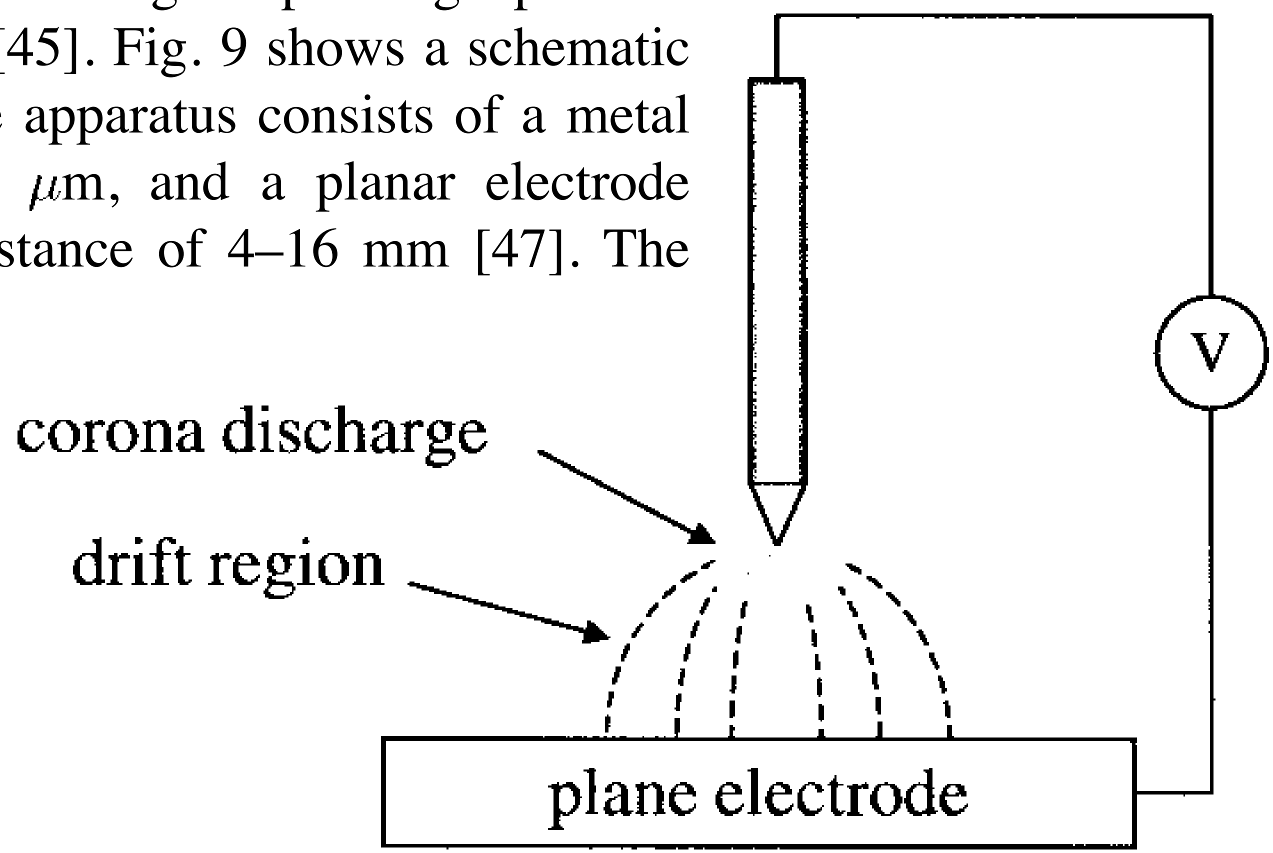


Fig. 9. Schematic of a corona discharge.

Shown in Fig. 10 is the dependence of the voltage on the current for a positive point-to-plane corona operating in air at 760 torr [5], [52]. The plasma ignites at a voltage of 2–5 kV and produces an extremely small current of 10^{-10}–10^{-5} A. Above 10^{-5} A, the voltage rapidly increases with current. This coincides with the generation of micro-arcs, or "streamers," that extend between the electrodes. A maximum voltage is recorded at about 5×10^{-4} A, where the device begins to arc. Coronas are operated at currents below the onset of arcing.

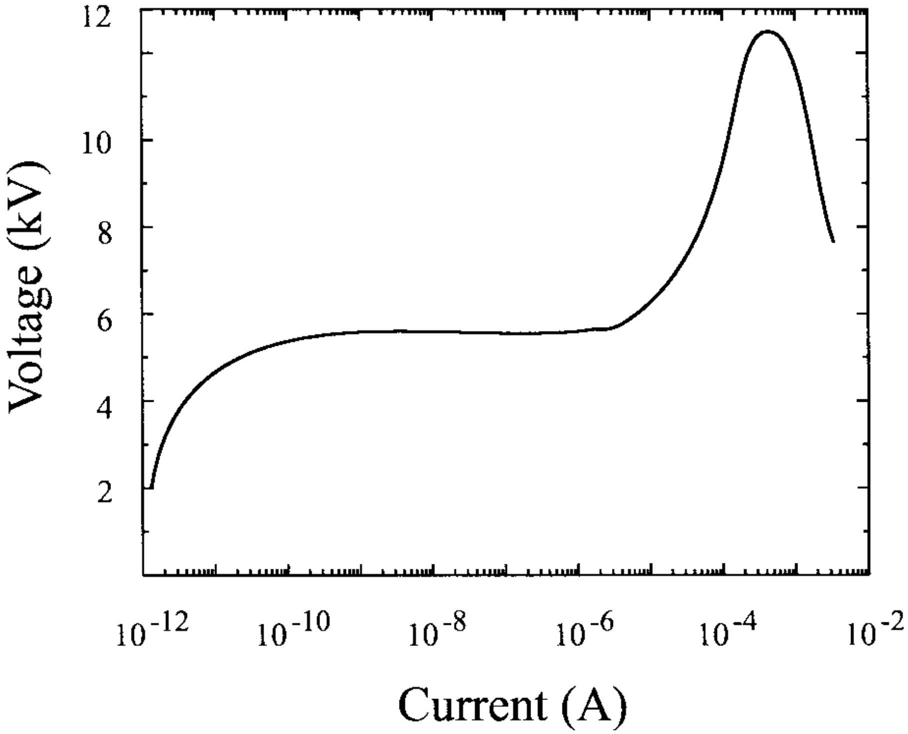


Fig. 10. Current–voltage characteristics for a positive point-to-plane corona discharge with a gap of 13 mm in 1 atm of air [5].

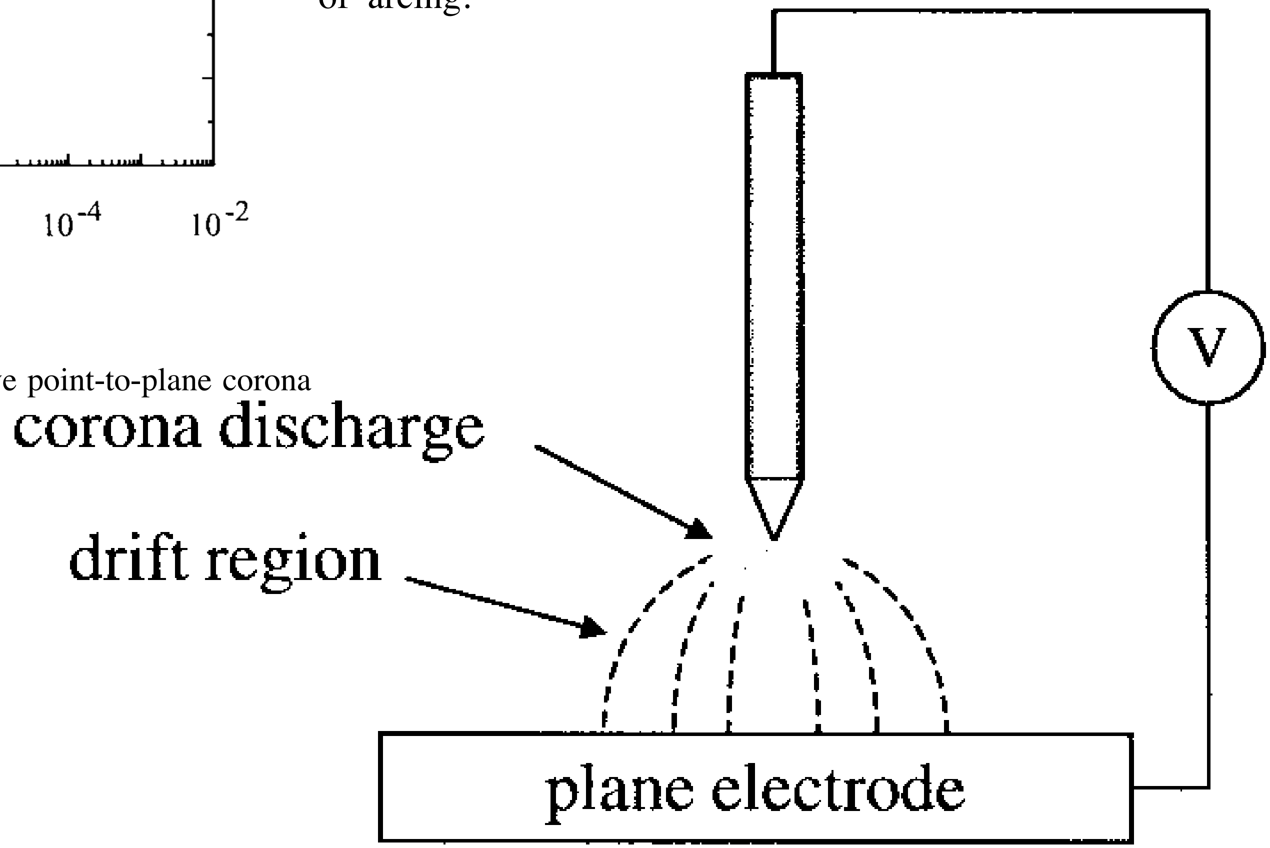


Fig. 9. Schematic of a corona discharge.

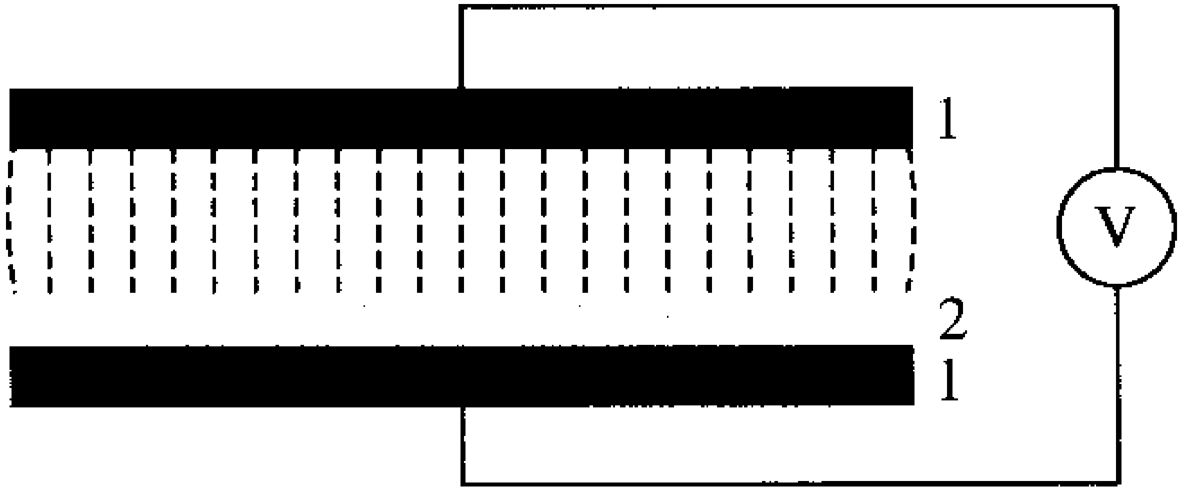
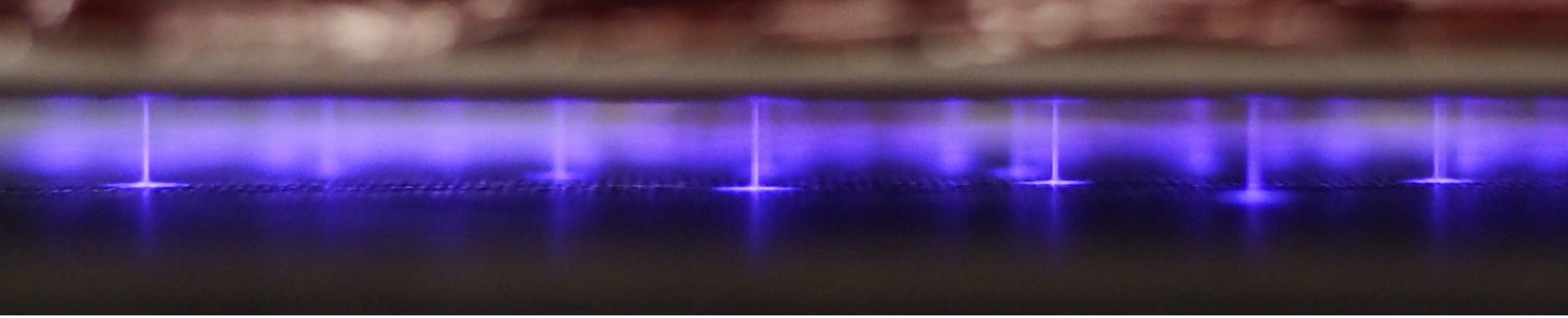
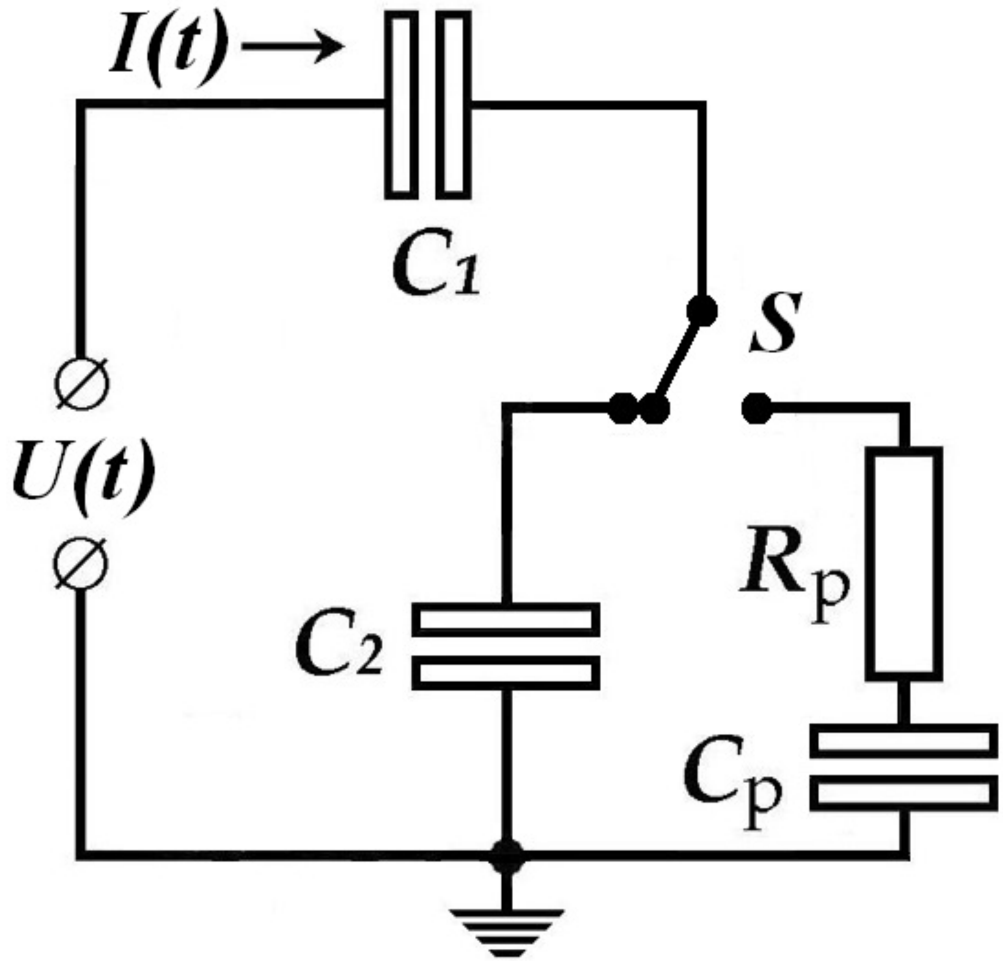


Fig. 12. Schematic of a silent discharge; (1) metallic electrodes and (2) dielectric barrier coating.

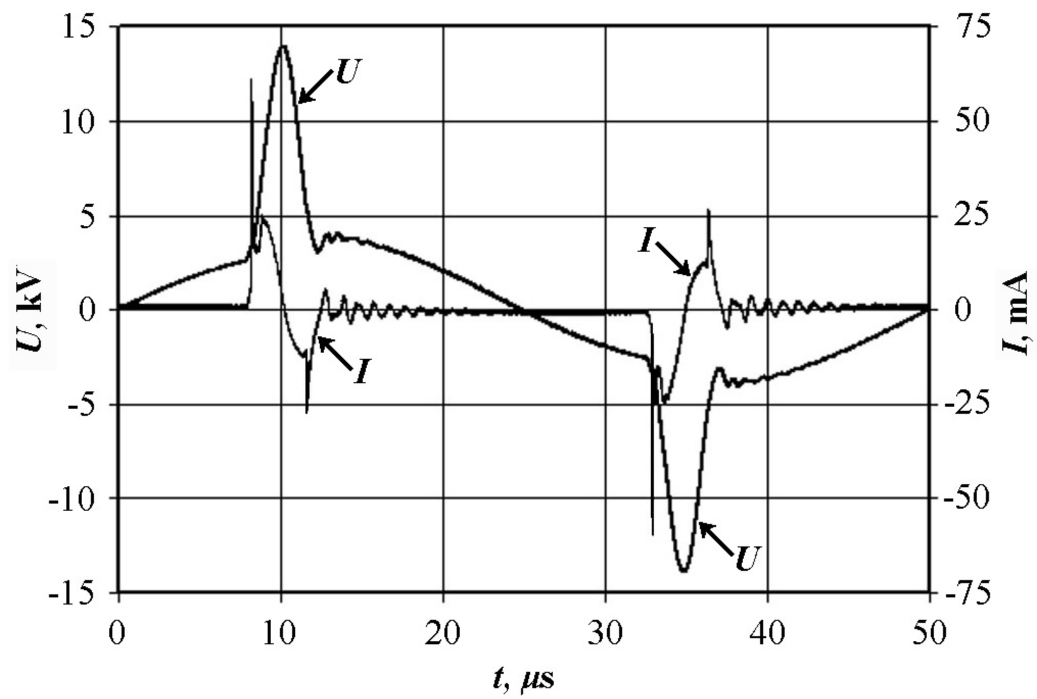
V. Dielectric Barrier Discharge

Dielectric barrier discharges are also called "silent" and "atmospheric-pressure-glow" discharges [6], [54]–[56]. A schematic of this source is shown in Fig. 12. It consists of two metal electrodes, in which at least one is coated with a dielectric layer. The gap is on the order of several mm, and the applied voltage is about 20 kV. The plasma is generated through a succession of micro arcs, lasting for 10–100 ns, and randomly distributed in space and time. These streamers are believed to be $\sim$100 μm in diameter and are separated from each other by as much as 2 cm [6], [56]. Dielectric barrier discharges are sometimes confused with coronas, because the latter sources may also exhibit microarcing.





I(t)
C1
S
U(t)
Rp
C2
Cp



U, kV
I, mA
t, μs
U
I
15
10
5
0
-5
-10
-15
75
50
25
0
-25
-50
-75
0
10
20
30
40
50

TABLE I
BREAKDOWN VOLTAGES OF THE PLASMA DISCHARGES

Source	V_b (kV)
Low-pressure discharge	0.2 – 0.8
Arc and plasma torch	10 – 50
Corona	10 – 50
Dielectric barrier discharge	5 – 25
Plasma jet	0.05 – 0.2

TABLE II
DENSITIES OF CHARGE SPECIES IN THE PLASMA DISCHARGES

Source	Plasma density (cm^{-3})
Low-pressure discharge	$10^8 – 10^{13}$
Arc and plasma torch	$10^{16} – 10^{19}$
Corona	$10^9 – 10^{13}$
Dielectric barrier discharge	10^{12} - 10^{15}
Plasma jet	10^{11} - 10^{12}

TABLE III
DENSITIES OF OXYGEN SPECIES IN THE PLASMA DISCHARGES

Source	Density (cm^{-3})		
	O^+, O_2^+, O^-	O	O_3
Low-pressure discharge	10^{10}	10^{14}	$<10^{10}$
Arc and plasma torch	10^{15}	10^{18}	$<10^{10}$
Corona	10^{10}	10^{12}	10^{18}
Dielectric barrier	10^{10}	10^{12}	10^{18}
Plasma jet	10^{12}	10^{16}	10^{16}

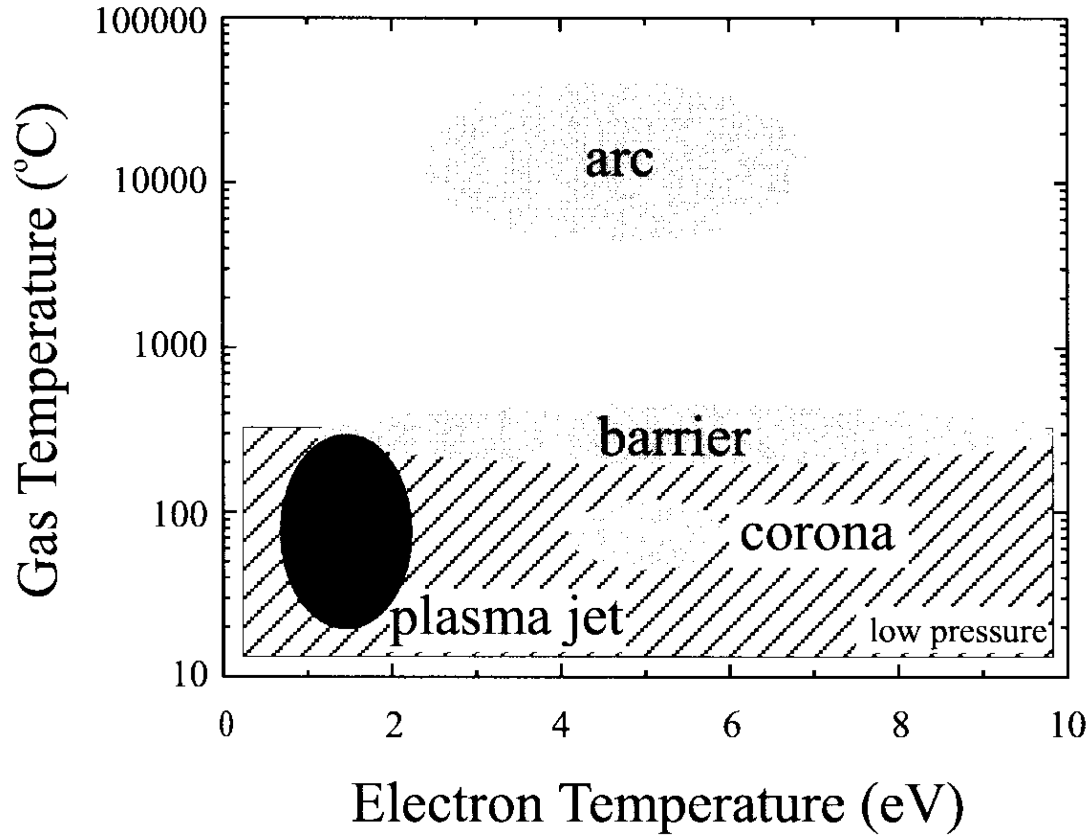


Fig. 18. Comparison of the gas and electron temperatures for different atmospheric-pressure plasmas versus low-pressure plasmas.

In the corona and dielectric barrier discharge, ozone is the main reaction product, whereas in the other plasmas, oxygen atoms represent a large fraction of the reactive species. In a low-pressure glow discharge the concentrations of ions and atoms are lower than in an atmospheric-pressure plasma. However, the impingement rate of these species on a substrate may be about the same in both cases, since the flux to the surface increases with decreasing pressure. Taking into account all the properties of the plasmas, it appears that the atmospheric-pressure plasma jet exhibits the greatest similarity to a low-pressure glow discharge. Consequently, this device shows promise for being used in a number of materials applications that are now limited to vacuum.

Microplasma jet at atmospheric pressure

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(Received 26 August 2006; accepted 22 October 2006; published online 30 November 2006)

A nitrogen microplasma jet operated at atmospheric pressure was developed for treating thermally sensitive materials. For example, the plasma sources in treatment of vulnerable biological materials must operate near the room temperature at the atmospheric pressure, without any risk of arcing or electrical shock. The microplasma jet device operated by an electrical power less than 10 W exhibited a long plasma jet of about 6.5 cm with temperature near 300 K, not causing any harm to human skin. Optical emission measured at the wide range of 280–800 nm indicated various reactive species produced by the plasma jet. © *2006 American Institute of Physics*.
[DOI: 10.1063/1.2400078]

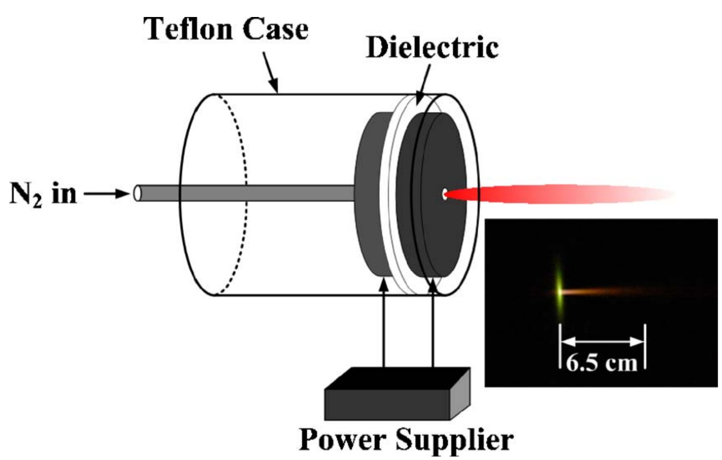

FIG. 1. (Color online) Schematic presentation of a simple nitrogen microplasma jet device at atmospheric pressure. The inset is the photograph of the microplasma jet at 6.3 lpm N_2.

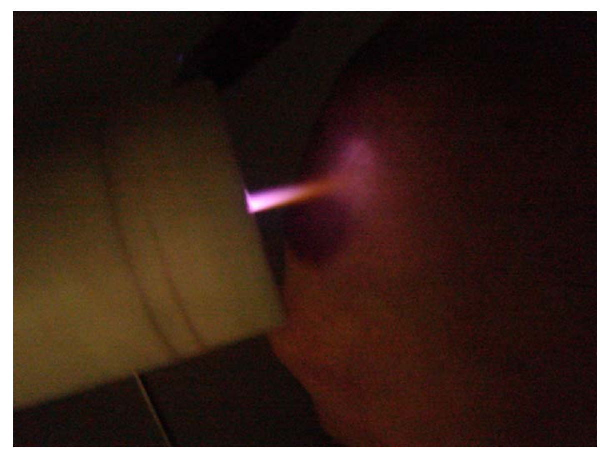

FIG. 2. (Color online) Photograph of the N_2 microplasma jet in contact with human skin.

PHYSICS OF PLASMAS **22**, 122005 (2015)

Microsecond-pulsed dielectric barrier discharge plasma stimulation of tissue macrophages for treatment of peripheral vascular disease

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Angiogenesis is the formation of new blood vessels from pre-existing vessels and normally occurs during the process of inflammatory reactions, wound healing, tissue repair, and restoration of blood flow after injury or insult. Stimulation of angiogenesis is a promising and an important step in the treatment of peripheral artery disease. Reactive oxygen species have been shown to be involved in stimulation of this process. For this reason, we have developed and validated a non-equilibrium atmospheric temperature and pressure short-pulsed dielectric barrier discharge plasma system, which can non-destructively generate reactive oxygen species and other active species at the surface of the tissue being treated. We show that this plasma treatment stimulates the production of vascular endothelial growth factor, matrix metalloproteinase-9, and CXCL 1 that in turn induces angiogenesis in mouse aortic rings *in vitro*. This effect may be mediated by the direct effect of plasma generated reactive oxygen species on tissue. © *2015 AIP Publishing LLC*.
[http://dx.doi.org/10.1063/1.4933403]

B. Microsecond pulsed DBD treatment

Treatment of the aortic rings was performed on glass slides with microsecond pulsed DBD (msDBD) plasma (Fig. 1). Plasma was produced by applying a voltage pulse of approximately 20 kV between the high voltage electrode and a grounded metal plate underneath the slide.[24,25] Aortic rings were at floating potential. Treatment time and gap distance were fixed at 10 s and 2 mm, respectively, and the frequency was internally controlled. Three frequencies, 50, 830, and 1000 Hz, were used for low, medium, and high plasma treatment. The energy per pulse of a single msDBD plasma discharge was measured and calculated using the methods stated in our previous work.[26] This was found to be 0.56 mJ/pulse, and the total energy delivered to the cells (dose) during treatment for the three frequencies are 0.3 mJ (50 Hz), 4.6 mJ (830 Hz), and 5.6 mJ (1000 Hz). Tissue was immediately transferred to a 24-well plate well containing matrigel.

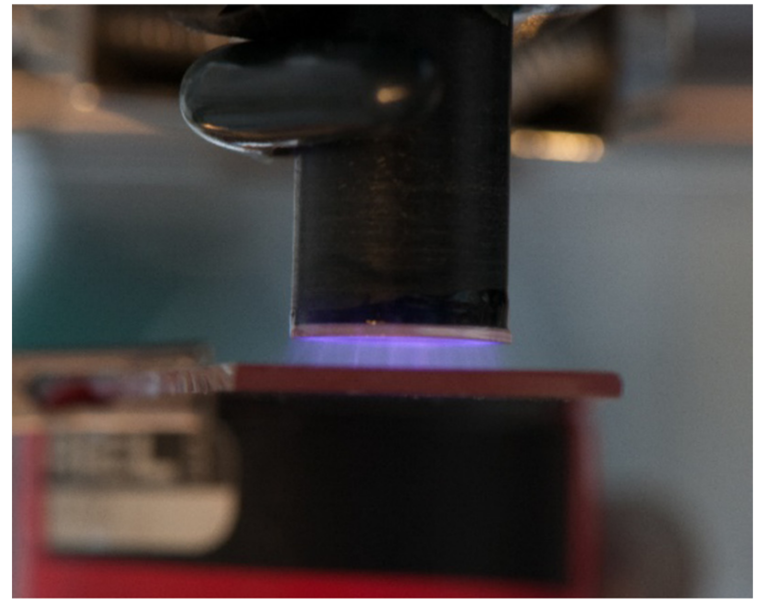

FIG. 1. Photograph of the microsecond-pulsed dielectric barrier discharge generated on top of a glass slide.