The One Atmosphere Uniform Glow Discharge Plasma (OAUGDP)—A Platform Technology for the 21st Century

J. Reece Roth, *Life Fellow, IEEE*, Sirous Nourgostar, *Student Member, IEEE*, and Truman A. Bonds, *Student Member, IEEE*

(Plenary Paper)

***Abstract*—Representatives from many industrial sectors are searching for more economic and ecologically sound technologies to meet regulatory and competitive pressures. Currently, the majority of industrial plasma processing is done with glow discharges at pressures below 10 torr. This tends to limit such applications to high-value items, as a result of the high capital cost of vacuum systems and the production constraints of batch processing. It has long been recognized that glow discharges would play a much larger industrial role if they could be generated at one atmosphere and in ambient air. A promising platform technology for plasma processing across many industrial sectors is the one atmosphere uniform glow discharge plasma (OAUGDP), a nonthermal normal glow discharge that operates in air (and other gases) at room temperature and atmospheric pressure. It generates active species useful for the sterilization, decontamination, and surface energy enhancement of films, fabrics, air filters, metals, and 3-D workpieces. This paper will survey exploratory research and development at the University of Tennessee's Plasma Sciences Laboratory on eight potential industrial applications of the OAUGDP that can be conducted at one atmosphere and at room temperature with air as the working gas.**

***Index Terms*—Adhesion, ashing, atmospheric pressure glow discharge, atmospheric pressure plasma, decontamination, Diesel soot removal, EHD, electrohydrodynamic flow control, electrohydrodynamics, etching, flue gas remediation, lighting devices, one atmosphere uniform glow discharge plasma (OAUGDP), plasma actuator, plasma illumination, plasma processing, sterilizable air filter, sterilization, wettability.**

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J. R. Roth and S. Nourgostar are with the UT Plasma Sciences Laboratory, Department of Electrical and Computer Engineering, University of Tennessee, Knoxville, TN 37996-2100 USA (e-mail: jrr@utk.edu; snourgos@utk.edu).

T. A. Bonds is with the UT Plasma Sciences Laboratory, Department of Electrical and Computer Engineering, University of Tennessee, Knoxville, TN 37996-2100 USA, and also with Atmospheric Glow Technologies, Knoxville, TN 37932-3723 USA (e-mail: tbonds@utk.edu).

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I. Introduction

PLATFORM technologies include such examples as materials handling, inventory control, welding, and microelectronic deposition and etching that are used in a wide range of industrial sectors and may include the aviation, aerospace, medical, healthcare, agricultural, food handling, automotive, printing, lighting, and textile industries. Those participating in research and development for these industries need to be aware of new platform technologies that can open up additional market opportunities, or improved manufacturing methods for current products. What is likely to be the next new platform technology? We would like to make a case that industrial plasma engineering at one atmosphere of pressure may become such a platform technology in the 21st century.

The industrial use of plasma has a history of well over 100 years, and examples such as ozone generation for public water supplies, arc welding, signage, fluorescent lamps, vacuum sputtering of thin films, and microelectronic deposition and etching are familiar industrial enabling technologies [1], [2]. Industrial plasma engineering has a promising future in these and other, entirely new areas for the following reasons: 1) Plasma-related methods can produce outcomes that can be accomplished in no other way; 2) Plasma-related methods can often accomplish industrially relevant results more efficiently and cheaply than competing technologies; and 3) Plasma-related processes usually accomplish results without producing large volumes of unwanted by-products or significant quantities of toxic waste materials. In addition to these major industrial, economic, and environmental advantages, plasmas can produce energetic active species at concentrations not possible by chemical means, and normal glow discharge plasmas operate at the Stoletow point, which is most energy efficient for generating ion–electron pairs. These characteristics of plasma processing have always been advantageous; they are becoming increasingly essential in the current, progressively more stringent regulatory atmosphere, and in an international competitive environment in which the United States must depend on its high tech skills to compete economically.

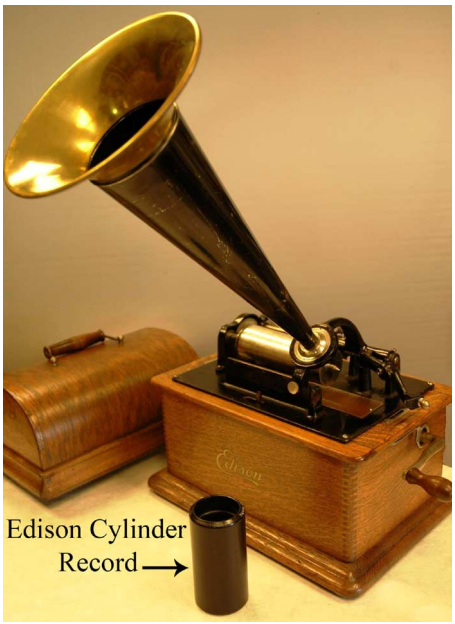


Fig. 1. Early Edison mechanical phonograph using cylindrical records rotating on a horizontal axis. The cylindrical recording has been removed from its mandrel and is shown resting vertically at the lower center.

To illustrate the first point concerning the ability of plasmas to accomplish tasks that can be achieved in no other way, we choose an example, due to Thomas Edison, from the earliest history of industrial plasma engineering. After inventing the phonograph in the late 1870s, Edison was faced with the problem of making multiple copies of the aluminum foil or soft wax master recordings. Circa 1900, he developed the phonograph illustrated in Fig. 1, which used cylindrical recordings like that shown in the lower center of the image.

Multiple copies were made with the vacuum plasma sputtering apparatus shown in Edison's patent of 1902 in Fig. 2. In this technology, the soft wax master recording was placed in a bell jar and rotated about a vertical axis by an external magnet, while gold sputtered from two high-voltage electrodes covered the wax with a thick enough coating to serve as a mold for multiple copies when the wax was removed. The resulting negative mold of the cylindrical recording was used to make multiple copies of the recording, like that shown in Fig. 1. This technology not only solved a technical problem intractable by existing methods, but was also the forerunner of a large vacuum coating industry.

With respect to the second major point above, the economic advantages of vacuum plasma treatment have been demonstrated by Rakowski [4], who examined in detail the modification of wool under industrial conditions, using both a conventional chlorination process, and a vacuum plasma treatment process. The objective of this technology is removal of the natural oils on wool fibers that prevent printing patterns on woolen cloth, so that it would behave more like cotton. Data from Rakowski's paper on the inputs of the conventional process are summarized in Table I.

The conventional chlorination process described in Table I uses relatively large inputs, among which are several chemicals that produce environmentally significant amounts of unwanted

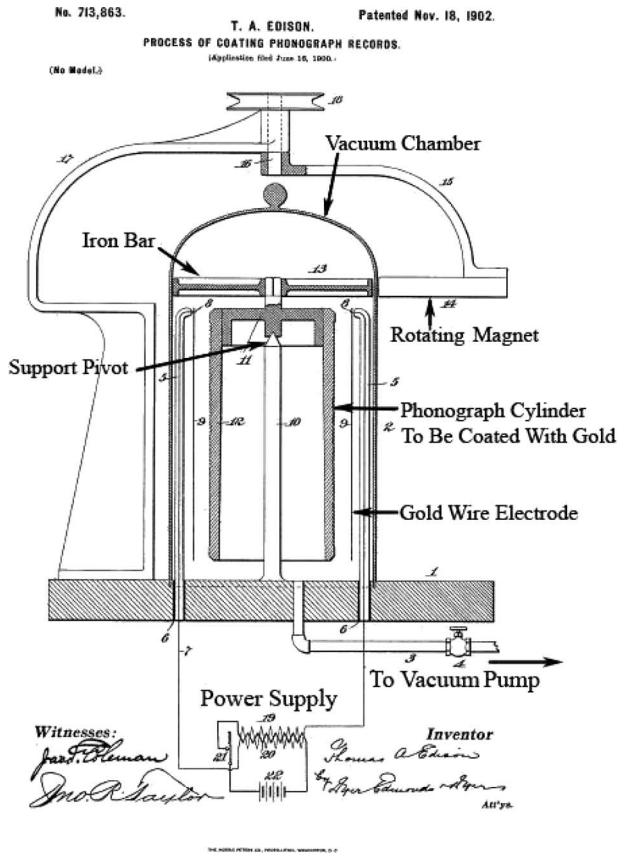


Fig. 2. Edison's 1902 patent on a plasma-assisted vacuum gold sputtering apparatus for making master molds for cylindrical phonographic recordings (from Waits [3]). The wax master cylinder rotates past the gold sputtering electrodes to build up a metallic mold for subsequent production of multiple copies.

TABLE I
CONVENTIONAL CHEMICAL CHLORINATION PROCESS TO ACHIEVE PRINTABILITY OF WOOLEN CLOTH [4]

Inputs	Inputs/ kg wool	Inputs for 120 tonnes/year
Water	225 liters	27,000 meter^3
Electrical energy	20.6 MJoules	2.47 TeraJoules
Sodium Hypochlorite	370 grams	44 Tonnes
Sodium Bisulphite	130 grams	16 Tonnes
Sulfuric acid	92 grams	11 Tonnes

by-products. These by-products, which include chlorine gas, are highly problematic from an environmental and regulatory point of view, and their reduction or elimination motivated Rakowski's work.

Rakowski proposed to reduce the amounts and cost of these inputs by vacuum plasma treatment of the wool with the vacuum RF glow discharge reactor shown schematically in Fig. 3. Rakowski's apparatus required four stages of vacuum pumping at the entrance and exit of the vacuum chamber, in order to maintain the vacuum while feeding the wool cloth through the plasma at realistic commercial speeds.

To demonstrate the advantages of vacuum plasma treatment over the conventional technology, Rakowski [4], examined in detail the power inputs for both the conventional chlorination process and his vacuum plasma treatment process, with the results shown in the first two lines of Table II.

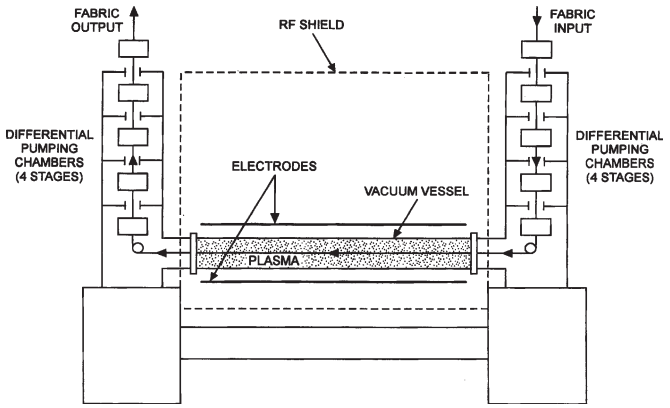


Fig. 3. Rakowski's apparatus for plasma treatment of continuous webs by a low-pressure RF glow discharge. Webs pass through four stages of vacuum pumping, and the RF discharge operates at 2 to 6 torr, with a wool production rate of 60 Kg/h.

TABLE II
POWER REQUIREMENTS TO TREAT 60 Kg/h OF WOOL [4]

Technology	CW power, kW	Input, MJ/kg wool
1.) Chlorination Process [4]	420	25.2
2.) Vacuum Plasma Exposure [4]	18 – 36	1.1 – 2.2
3.) Atmospheric Plasma Exposure	1 - 4	0.06 – 0.24

Not only can the inputs of water and chemicals be virtually eliminated by plasma processing, but also lines 1 and 2 of Table II show that the energy and power inputs required to maintain a commercially viable processing rate can be reduced by a factor of ten or more with the use of a vacuum plasma.

One can use Rakowski's data in line 2 of Table II to estimate the energy cost of plasma treatment of wool at one atmosphere. If a one atmosphere uniform glow discharge plasma (OAUGDP) is used, the power input to the vacuum pumps is not needed, and the dominant energy sink is the power required to generate the RF plasma, from 1 to 4 kW. The third line of Table II is our estimate of the required inputs, and indicates that glow discharge treatment at one atmosphere further reduces the energy cost of the wool treatment for printability by a factor of more than 100 compared to the conventional chlorination process, and by more than a factor of 10, compared to Rakowski's vacuum plasma treatment process.

To illustrate the third major point made above, the ability of plasma processing to reduce or eliminate the production of toxic or unwanted by-products, We take the example of Silicon Valley in California, at the southern end of San Francisco Bay. Fig. 4 shows the location of Federal Superfund toxic waste sites circa 1991, most of which were associated with the underground storage of spent solutions used in early microelectronic wet chemical etching operations [5]. This is said to have been the largest concentration of Superfund sites in the United States, one of which, the IBM site at the lower right, had an underground waste plume that was estimated to cost $100 M to clean up.

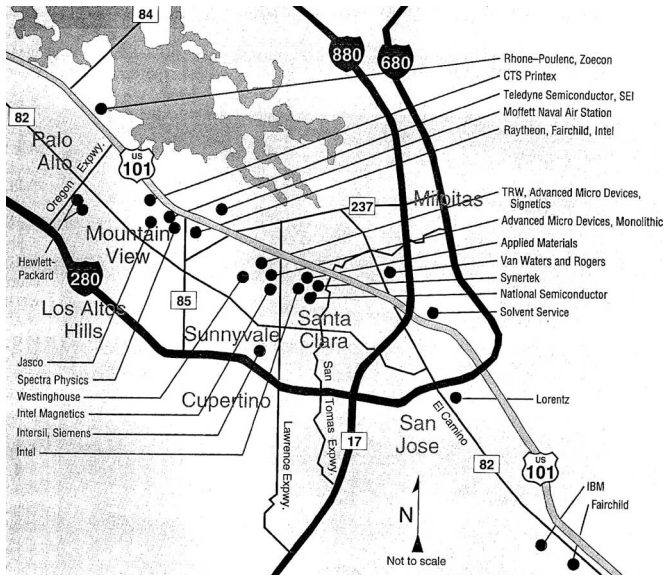


Fig. 4. Map of Silicon Valley at the southern end of San Francisco Bay in California, showing the location of Federal Superfund toxic waste sites circa 1991, most of which were associated with the underground storage of spent solutions used in early microelectronic wet chemical etching operations [5] 2001 IEEE.

When "dry" plasma etching replaced "wet" chemical etching after circa 1980, the production of toxic and unwanted byproducts by microelectronic chip fabrication virtually ceased, making microelectronic chip fabrication one of the cleanest of high tech industries.

It should be clear, however, that glow discharges have certain disadvantages for industrial plasma processing. Vacuum glow discharges require a vacuum system, and this in turn makes necessary batch processing of workpieces, a serious cost in the textile and paper industries, where fast-moving webs are best handled by continuous processing. In addition, vacuum systems have significant power and maintenance costs, and the physical processes relating inputs to outputs of industrial glow discharge processing are often not well understood.

Many of these disadvantages can be overcome by operating a uniform normal glow discharge in air at atmospheric pressure. Even in such a case, one must deal with the production of ozone and ultraviolet radiation, and the power supply technology needed for such reactors is not available off-the-shelf.

II. ONE ATMOSPHERE UNIFORM GLOW DISCHARGE PLASMA (OAUGDP)

A factor that may promote industrial plasma engineering as an enabling platform technology is the recent development of plasmas, including glow discharge plasmas, which can operate in a stable manner in air and at one atmosphere. The OAUGDP is such a plasma, and will be discussed as an example.

A. Historical Development of the OAUGDP

In 1933, von Engle *et al.* [6] appear to have been the first to report the operation of a dc normal glow discharge in air at one atmosphere. However, their procedure required initiation of the discharge under vacuum, followed by a gradual increase

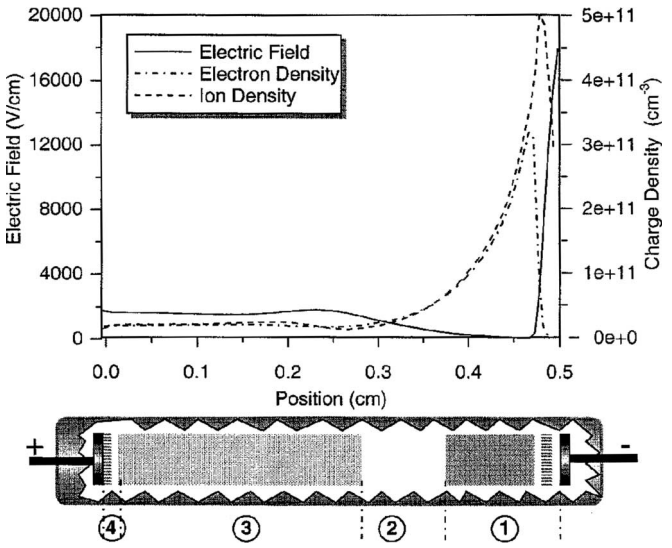


Fig. 5. Upper graph: Computational simulation of plasma parameters in a parallel plate, OAUGDP in helium by Ben Gadri [11], [13]. The lower diagram shows the corresponding regions of a normal glow discharge: 1—Cathode region, including negative glow; 2—Faraday dark space; 3—positive column; and 4—Anode dark space.

in pressure to one atmosphere. It also required aggressive cooling of the cathode to suppress the glow-to-arc transition. This discharge was not stable with respect to the glow-to-arc transition at one atmosphere, and it has found few, if any, applications.

The cathode heating responsible for the glow-to-arc instability of the von Engle discharge arises from ion bombardment and heating of the cathode. The ion trapping mechanism was conceived [7]–[10] to avoid cathode heating, and is achieved by applying RF to the electrodes at a frequency such that ions, but not electrons, are trapped between the electrodes [1], [2], [10]. A dielectric plate on at least one of the electrodes is used to further suppress the glow-to-arc transition. This transformation of the von Engle discharge from dc to RF greatly reduces cathode heating by ion bombardment, reduces sputtering and erosion of the electrodes, reduces contamination of the plasma, stabilizes the plasma against the glow-to-arc transition, and provides a form of electrodynamic trapping that increases the ion and electron number density available for Lorentzian collisions and active species production. This type of discharge was called the OAUGDP [10].

Numerical simulations of the OAUGDP by Ben Gadri [11] and measurements of axial luminous intensity by Massines *et al.* [12], [13] in helium gas, showed that the OAUGDP has the classic structures of the dc normal glow discharge, and that these reverse with each half-cycle of the RF. These structures are indicated in Fig. 5.

The identification of the OAUGDP as a normal glow discharge is valuable from a plasma-physical and a phenomenological point of view, because it brings into play nearly two hundred years of accumulated observations and understanding from electrical discharge research [1], [2]. An important example is knowledge that the OAUGDP, like all normal glow discharges, operates at the Stoletow point [1, Sec. III, IV, VIII]. This provides assurance that the generation of ion–electron pairs at one atmosphere in the OAUGDP cannot be done more efficiently, an important consideration in many applications. For air, this minimum energy cost is 81 eV per ion–electron pair formed in the plasma.

B. Research and Development on the OAUGDP at the University of Tennessee (UT)

The OAUGDP, developed at the UT's Plasma Sciences Laboratory [7]–[10], [14]–[16], will be used as an example of the industrial potential of glow discharge plasma operation at one atmosphere. At UT, exploratory investigations have been conducted on a variety of prospective industrial applications of the OAUGDP, which include increasing the surface energy and wettability of fabrics, films, and solid surfaces [17]–[30]; sterilizing surfaces for healthcare and food processing [31]–[42]; decontaminating surfaces compromised by chemical or biological warfare agents [35]–[44]; a sterilizable air filter to deal with the sick building syndrome [45], [46]; removal of soot and volatile organic compounds (VOCs) from Diesel engine exhaust [14]; mercury-free atmospheric pressure fluorescent lamps [14]; stripping of photoresist and directional etching of possible microelectronic relevance [14], [20], [21], and plasma chemical vapor deposition at one atmosphere [28], [47], [48]. In addition to these applications, plasma aerodynamic flow control and flow attachment to airfoils have been reported in air at one atmosphere [49]–[59], and other research groups have used atmospheric plasmas to extend the shelf life of thin-skinned fruits and to kill insects.

The OAUGDP is not a corona discharge, a filamentary discharge, a dielectric barrier discharge (DBD), or an ozonizer [14], [24]. The latter three depend on avalanching and their durations are measured in tens of nanoseconds, freezing the atmospheric chemistry at ozone production. The electron number density, energy distribution function, etc., are time as well as space dependent, and follow the RF cycle. The highest density phase of the OAUGDP lasts microseconds to tens of microseconds [11]; this allows the chemistry of an air plasma to produce atomic oxygen and highly oxidizing species other than ozone. To generate an OAUGDP, one must operate with an rms voltage, frequency, and gap spacing that produce ion trapping, but not electron trapping, between the electrodes [1]. At any point in the RF cycle, the instantaneous discharge between the electrodes has the characteristics of the dc normal glow discharge, including the negative glow, the Faraday dark space, the positive column, and a cathode region in which the electric field and charge density obey Aston's law [11, Fig. 5].

C. Physics and Phenomenology of the OAUGDP

The electric fields employed to create the OAUGDP are normally less than ten kilovolts per centimeter in air and 2–3 kV/cm in argon and helium, values too low to achieve dc electrical breakdown (sparking) of the operating gas at atmospheric pressure. In [1, Sec. II, V, XII], it was shown that the critical RF driving frequency ν_o, above which the uniform glow discharge should build up in the plasma volume as the result of ion trapping, is a function of the electrode gap spacing, rms voltage, and RF frequency. This trapping frequency is

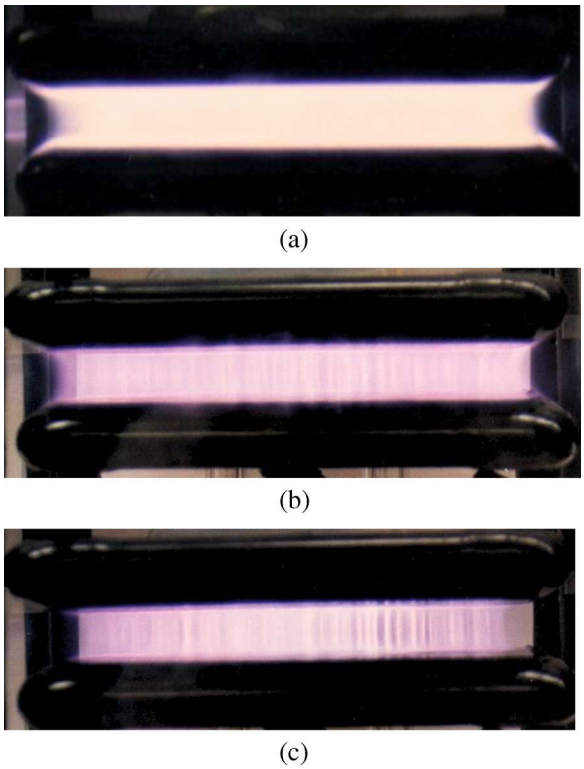


Fig. 6. Uniform and filamentary operation of the OAUGDP in helium gas at one atmosphere at RF frequencies of (a) 20, (b) 40, and (c) 60 kHz.

determined by the mobility drift of the ions in the oscillating RF electric field that traps them between the electrodes during an RF cycle. During ion trapping, the electrons are free to travel to the dielectric covering on the electrodes, where they recombine, or build up a surface charge that carries the discharge through the RF current zero into the next half-cycle [11]–[13]. If the RF driving frequency is above the ion trapping frequency, and so high that it also traps electrons as well as ions between the electrodes, then the plasma becomes polarized, and undergoes an instability that results in the formation of numerous coarse filaments. This instability may be related to the negative corona instability [60], [61].

1) Uniformity of Appearance of the OAUGDP: In this section, we discuss the visible uniformity of the OAUGDP and in the next section we discuss its uniformity of effect down to the nanoscale by reference to scanning electron micrographs (SEMs) of surfaces used as witness plates for filamentary discharge activity.

The visual uniformity of an OAUGDP operating in a parallel plate configuration is illustrated in Fig. 6, which shows three images taken of the MOD I OAUGDP reactor, operating in helium at one atmosphere with a dielectric barrier coating on both electrodes, and an applied RF voltage of 4.5-kV rms at three frequencies. As the RF frequency was raised from below 1 kHz, the discharge first appeared as a few coarse filaments, then became brighter and more uniform, to the point where it was uniform to the eye at about 2–3 kHz. As the frequency was further raised, it remained uniform to the eye until 30 kHz, as shown in Fig. 6(a). Above this frequency, however, the appearance of the discharge became progressively less uniform, with increasing gaps and more coarse filaments, as shown in Fig. 6(b) and (c). These filaments were as much as 2 mm in diameter, much larger than the submicrometer scale microfilaments associated with avalanching in DBDs. In helium and argon, the plasma initiated at electric fields from 2 to 3 kV/cm; in air, an electric field at least 8.5 kV/cm was required, and the frequency range over which the plasma was uniform was much more limited.

Coarse filamentation associated with the OAUGDP occurs at high electric fields and/or at high frequencies when the electrons, as well as the ions, are trapped between the electrodes. Plots of power versus frequency or voltage for the OAUGDP show no discontinuity at the uniform-to-filamentary boundary. Filaments may be anchored to fine points or asperities, and may range from 0.05 to 5 mm in diameter. They are undesirable, and lead to nonuniformity of effect, pin-holing, cratering of the surface, and other forms of surface damage that are illustrated below.

The coarse filaments of the OAUGDP appear to be related to the "Negative Corona Instability," first described by Peek in 1915 [60], and later discussed by Cobine [61]. A satisfactory theory of the negative corona instability that explains the equal spacing of the corona/filament discharges, or the physical processes responsible for the quantization/filamentation of the discharge, has not yet been put forward.

The coarse filaments of the OAUGDP are not to be confused with the microfilaments of the DBD. The DBD features higher electric fields than the OAUGDP, and its charge carriers are created by electron avalanche. The DBD plasma also features nonuniform, microfilaments, 10 to 500 nm in diameter, which occur in random locations. These microfilaments have short lifetimes, 1 to 50 ns, too short for many chained plasma-chemical reactions that produce important active species in longer lived discharges, such as the OAUGDP.

Filamentation in parallel-plate OAUGDP reactors may be avoided by staying within the operating envelope of voltage and frequency that produces a visibly uniform plasma in the gas used. Helium and argon are easy to make uniform: air, and especially humid air, is much more difficult. In air, the relative humidity should be kept below 14% by using dry air, or recirculating the air through the plasma until dry. Negative ion formation, particularly OH^-, should be avoided by keeping the humidity at low levels. Electrophilic species (those that attach electrons) should be avoided, as they appear to promote filamentation, and reduce the operating envelope in which a uniform plasma can be generated. One should avoid asperities on the electrode or dielectric, rough edges around the electrode edges, and dielectric configurations that lead to electric field concentrations. The edges of the electrodes should be rounded off so that the surface electric field at the edge is less than the electric field between parallel electrode plates. In air plasmas, gas flow across the plasma (normal to the electric field) tends to suppress filamentation. Also in air plasmas, it becomes progressively more difficult to prevent filamentation as the electrode gap increases in width, and almost impossible to do so for gaps larger than 5 mm. To put most of these phenomena on a scientific basis, research on the negative corona instability is needed.

2) Uniformity of Effect of the OAUGDP: The image in Fig. 6(a) reveals only the apparent, visible luminosity of the

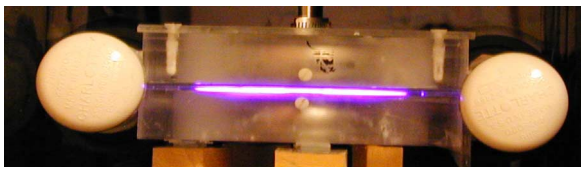


Fig. 7. MOD VI OAUGDP reactor operating in air at one atmosphere of pressure. Recirculating air flows from left to right.

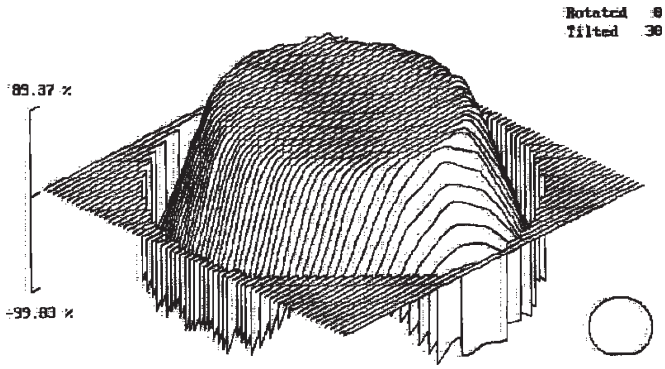
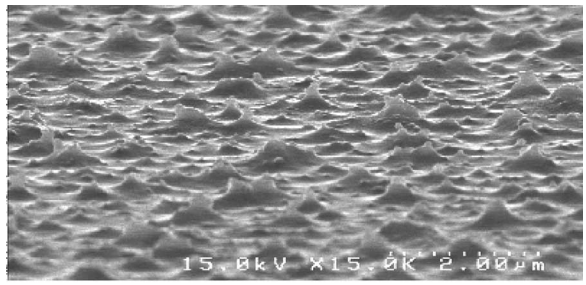
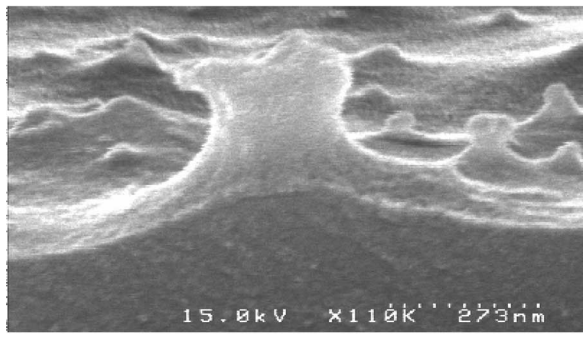


Fig. 8. Isometric contour plot of the etched surface of a uniform coating of photoresist on a 20-cm-diameter silicon wafer (outer circle) directly exposed to an air OAUGDP for 5 min in the MOD VI reactor of Fig. 6. The uniformity of depth across the 15-cm etched diameter is less than 5%; and the etching rate was 270 nm/min. (Wafer and topographic analysis courtesy of Eaton Corporation).



(a) Large scale topography



(b) Small scale topography

Fig. 9. SEMs of photoresist etched for 5 min in the presence of surface dust in the MOD VI reactor operating in the OAUGDP mode with air flow from left to right. The approximate distance across the width of the above images is (a) 7.9 μm, and (b) 1.1 μm. Note the absence of microdischarge pits and the presence of vertical etching.

plasma. For industrial applications, one would like, in addition, to show that the OAUGDP is uniform in its effect on workpieces at the microscopic scale. Such data were produced in the course of research programs conducted with other objectives. In one such program, we exposed several 20-cm-diameter silicon wafers, coated with a proprietary photoresist, to an air OAUGDP in the MOD VI reactor of Fig. 7 for various durations, for visibly uniform OAUGDP conditions, and under conditions for which the plasma was filamentary.

The MOD VI OAUGDP reactor operating with a uniform visual appearance in air at one atmosphere is shown in Fig. 7. This reactor was designed to expose samples to the OAUGDP for biological (sterilization) or surface energy testing in two principal modes of operation: direct exposure, in which the workpiece is placed on an electrode and directly exposed to the plasma; and recirculating remote exposure, in which the workpiece is located outside the plasma volume, and active species from the plasma are convected over its surface by a gas flow that recirculates through the OAUGDP multiple times.

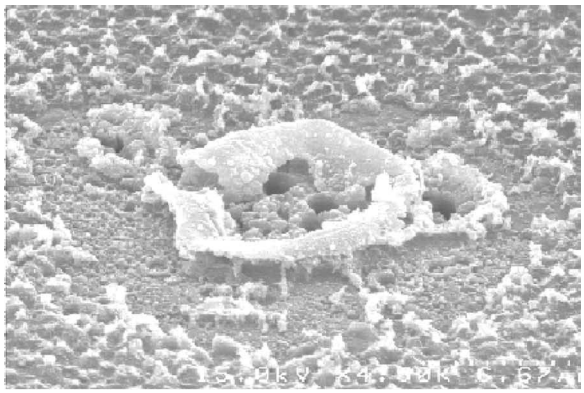
During etching tests on photoresist, the 15-cm-diameter lower electrode of the MOD VI reactor was covered by a 20-cm-diameter silicon wafer with the photoresist directly exposed to the plasma. After adjustment of the flow velocity, flow geometry, RF frequency, and rms voltage, we obtained the result shown in Fig. 8, a topographical representation of the average depth of photoresist removed during 5 min of OAUGDP exposure. The macroscopic uniformity of stripping across the 15-cm-diameter of the plasma was a commercially acceptable 5%, and the stripping rate was 270 nm/min.

An additional requirement for microelectronic stripping is that the process not deposit dust or contaminants on the wafer. This is normally assured by maintaining clean room conditions, a requirement not met in our laboratory. Fig. 9 is a SEM of the etched surface depicted in Fig. 8 under uniform OAUGDP conditions, which reveals small ($\approx$ 50 nm) grains of dust that settled on the surface of the photoresist. The corrugated, parallel structures supporting the bottom of the particles are aligned with the gas flow in the MOD VI reactor. It should be noted that under these uniform OAUGDP conditions, the surface of the wafer is free of the pitting or pin-holing associated with filamentation and/or DBD operation.

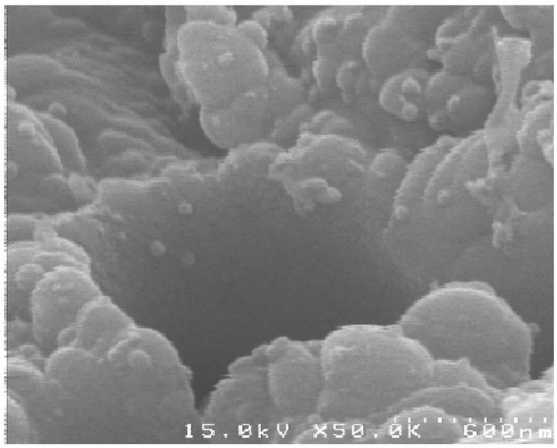
When the MOD VI reactor was operating in a visibly filamentary/DBD mode, SEMs of the surface revealed the features shown in the images of Fig. 10. These features are consistent with surface damage at the root of microfilaments in the DBD mode of operation, where the local energy flux is highest. The pitting and pin-holing evident in Fig. 10 are not apparent in the SEM images taken in the uniform plasma, Figs. 6(a) and 7.

III. Potential Applications of the OAUGDP

Since 1992, we at the UT's Plasma Sciences Laboratory have conducted a series of exploratory research and development tasks with various OAUGDP reactor configurations. These tasks have been designed to test the atmospheric glow discharge hypothesis: "Any plasma processing task possible with a glow discharge in vacuum can also be performed by a glow discharge at one atmosphere, provided that long mean free paths are not required." These tasks have included: 1) increasing the surface energy of fabrics, films, and solid materials; 2) plasma etching of surfaces of microelectronic relevance at one atmosphere; 3) sterilizing surfaces for healthcare, medical, and food processing applications; 4) decontaminating surfaces compromised by



(a) Surface damage at filament root.



(b) Pitting/pin-holing at filament root.

Fig. 10. SEMs of photoresist etched in the MOD VI reactor operating in the filamentary OAUGDP mode with air flow from left to right. The approximate distance across the width of the above images is (a) 25.8 μm, and (b) 2.4 μm. Note the pits formed by the roots of microdischarges and/or filaments.

chemical and biological warfare agents; 5) the feasibility of a sterilizable air filter to deal with the sick building syndrome; 6) removal of soot and VOCs from Diesel engine exhaust; 7) the feasibility of a mercury-free atmospheric pressure fluorescent lamp; and 8) EHD plasma actuators for subsonic plasma aerodynamics, flow acceleration, and boundary layer control. These eight tasks are discussed below.

The reactor configurations used in this research and development include the parallel-plate MOD I reactor, illustrated in Fig. 6, the MOD VI parallel-plate reactor illustrated in Fig. 7, the MOD VIII roll-to-roll reactor illustrated in Figs. 14 and 15 below, and the exploratory testing reactor shown in Fig. 11. The latter reactor consists of a grounded baseplate as the lower electrode, covered by a circa 1-mm-thick dielectric (quartz or Pyrex) barrier, and a metallic sample or workpiece at high RF voltage as the upper electrode, spaced above the lower electrode by one or more microscope slides.

A. Increasing the Surface Energy of Fabrics, Films, and Solid Materials

Paired comparisons were made of direct exposure and recirculating remote exposure of workpieces to the OAUGDP active species in the MOD VI reactor of Fig. 7, and it was found that direct exposure is much more effective in increasing the surface energy of materials than single or multiple pass remote exposure. In contrast, it was found that sterilization of surfaces by remote exposure remains highly effective by comparison with direct exposure to the plasma, and that microbial killing/sterilization is more effective for multiple-pass recirculating remote exposure than for single-pass remote exposure. The active species responsible for sterilization build up (or at least become more effective) upon recirculation of the working gas through the plasma.

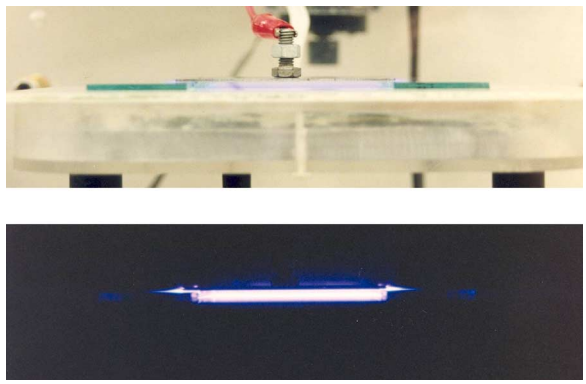


Fig. 11. Static sample test in the parallel-plate exploratory testing OAUGDP reactor configuration for direct exposure of a bare metal workpiece as the upper electrode.

It was found in static sample tests that direct exposure to an air OAUGDP is an effective way to increase the surface energy and wettability of fabrics, films, fibers, and such solid materials as metals, polymers, paper, and plastics from values of 30–40 dyn/cm up to values of 70 dyn/cm [14]–[30]. Contact angles below ten degrees (surface energies higher than circa 70 dyn/cm) can be achieved with less than 1 s of direct exposure to an air plasma in the MOD VI OAUGDP reactor shown in Fig. 7. The high surface energies are not durable in most cases. When samples are left exposed to the laboratory environment, their surface energy decreases to 50 dyn/cm over periods of days to weeks. If oxygen or other polar groups are added to polymeric materials, their wettability can be durable [19].

1) Contact Angle Measurements of Small Static Samples: The contact angle of polyethylene teraphthalate (PET) film is shown in Fig. 12 as a function of the duration of direct exposure to an air OAUGDP in the MOD VI reactor of Fig. 7, for selected times after exposure (the ageing effect). Durable contact angles below 25° for periods of more than a year have also been observed in OAUGDP treated meltblown polyurethane fabrics [25].

The physical process responsible for increasing the surface energy is believed to be the removal of the last few tightly adsorbed monolayers of surface contaminants by direct plasma exposure. After this point, the substrate material is etched by the active species. The etching of the surface of individual fibers in a meltblown polypropylene (PP) fabric exposed to a CO_2 plasma in the MOD I reactor is illustrated in Fig. 13. Particularly interesting in the image of Fig. 13(b) is the absence of shadowing. These and similar SEM images of plasma etched fibers show that etching takes place uniformly around the circumference of each fiber, an important factor when the role

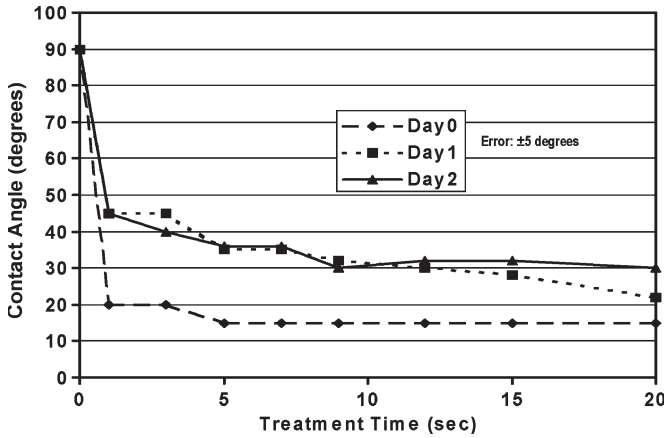


Fig. 12. Static sample test showing the decrease of contact angle (increase of surface energy) of PET film as a function of duration of direct exposure to an air OAUGDP in the MOD VI reactor of Fig. 7, and the aging effect for selected times after exposure.

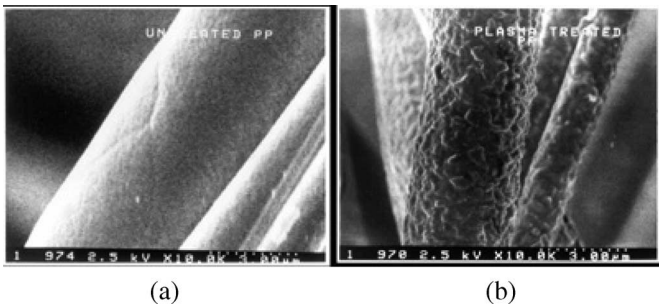


Fig. 13. SEM of PP fibers. (a) untreated, and (b) fibers exposed for 30 s to an OAUGDP CO_2 plasma. Note three-micrometer fiduciary scale at the lower right.

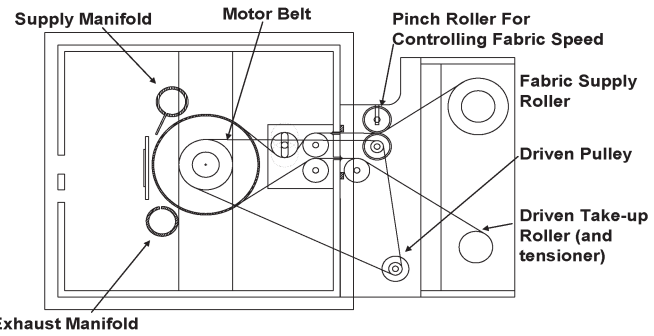


Fig. 14. Roll-to-roll web path and location of drive belts on the MOD VIII reactor. The fabric feed system is a dual motor design, allowing separate control of web speed and tension.

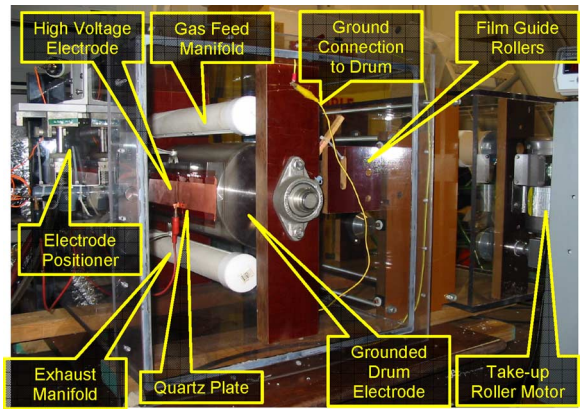


Fig. 15. Digital image front view of the MOD VIII roll-to-roll web treatment reactor based on the OAUGDP. Note rotating drum and gas supply and exhaust manifolds.

of the active species is to sterilize the fabric, prepare it for dyeing, or for use in a composite material.

This surface etching mechanism is consistent with the observation that iron alloys directly exposed to an air OAUGDP in the exploratory testing reactor of Fig. 11 form a coating of rust within a few minutes of exposure, presumably because removal of the oils/contaminants that protect the surface allow oxidation of the iron within this abnormally short duration. During our past studies, Teflon has been made wettable after a 5-min exposure to an air OAUGDP, with a water contact angle of 20°.

The low contact angles (high surface energies) imparted by direct exposure to the OAUGDP can make it possible to use water-based inks for printing, to improve the adhesion of paints on plastics, to increase the adhesion of electroplated layers to metals, and to make fabrics wettable and wickable. Applications to the improvement of composite materials such as automobile tires, Fiberglas, and aircraft fuselages should be possible.

2) MOD VIII Roll-to-Roll OAUGDP Reactor: Previous surface treatment studies conducted at the UT Plasma Sciences Laboratory have consisted of static sample studies in batches, or as single workpieces. In order to move on to more industrially relevant roll-to-roll web treatment technology, we designed and constructed the MOD VIII OAUGDP roll-to-roll reactor, a schematic of which is shown in Fig. 14. This reactor allows continuous operation with webs or films at one atmosphere pressure with air and other gases.

In this reactor, a moving substrate on the rotating drum passes through the plasma region, allowing motional averaging to improve uniformity of effect in the direction of web motion. This motion also helps prevent the formation of filamentation-induced pinholes, and addresses real world issues of high-speed industrial processing of webs. The independent variables being optimized are web/film feed speed, web/film tension, workpiece temperature, plasma uniformity, applied RF voltage, RF frequency, minimum gap distance, and gas flow uniformity, angle, and rate. Diagnostic measurements include time-dependent current and voltage analysis, visual inspection of the plasma volume, and "witness plate" methods of assessing surface treatment effects, particularly pin-holing.

The schematic of the MOD VIII reactor in Fig. 14 shows the roll-to-roll web path and the location of the drive belt. The fabric feed system is a dual motor design, allowing separate control of web speed and tension. The primary treatment drum turns counterclockwise, is grounded, is polished metal, and is 20 cm in diameter. The quartz plate and RF electrode are shown to the left of this drum. A digital image of the MOD VIII reactor is shown in Fig. 15. A nonuniform electric field exists between the quartz plate and the rotating drum, and a uniform plasma

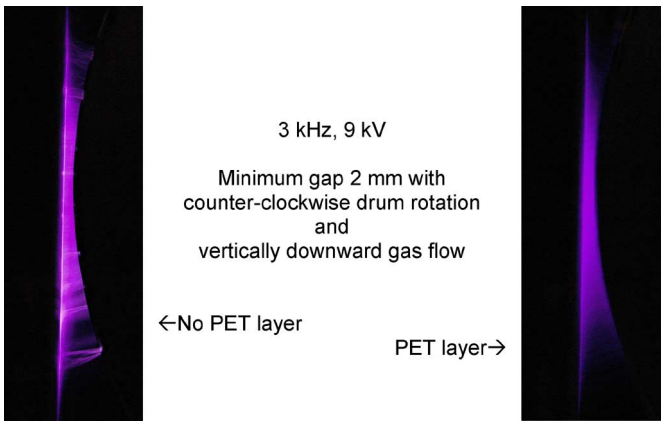


Fig. 16. RF voltage, current, power, and plasma appearance in the plasma treatment region with a 290-cm^2 electrode behind a 1.2-mm-thick quartz dielectric sheet. The rotating cylinder is grounded. Shown on the left is a filamentary OAUGDP with bare rotating drum; on the right, a uniform OAUGDP with the grounded drum covered by a PET film.

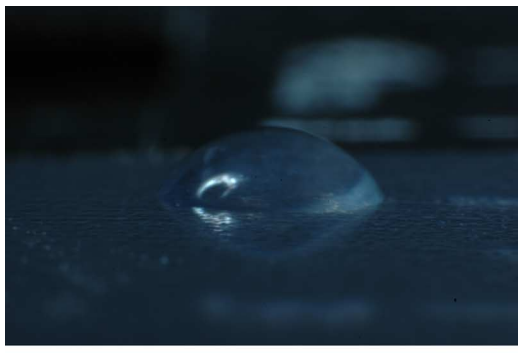
exists along the axial length of the rotating drum, resulting in a power density gradient in the azimuthal direction. The gas feed system blows air or other feed gases from the top, parallel to the fabric motion, into the plasma volume. The minimum gap between the grounded rotating drum and the 1.0-mm-thick quartz plate is $d = 2$ mm.

In Fig. 16(a), at the left-hand side, a filamentary OAUGDP having suboptimal plasma density is shown, and with the grounded drum bare. In Fig. 16(b), on the right-hand side, a uniform OAUGDP with optimal plasma density is shown, with the grounded drum covered by a thin PET film. The grounded drum rotates counterclockwise, and the air flows from the top to the bottom of the plasma.

3) Surface Energy Enhancement by the MOD VIII Roll-to-Roll Reactor: The sessile liquid drop test was used to measure the contact angle of water drops on the surface of polyethylene terephthalate (PET) film, a measure of wettability directly related to surface energy. Contact angles were measured from photographic enlargements of water drops such as those illustrated in Fig. 17, on the film surface after plasma treatment. A contact angle less than 20° represents a very wettable surface. Fig. 17 shows two characteristic photographs of water droplets on a PET surface before and after plasma exposure.

The contact angle, exposure time, and fabric speed from some early experiments with the OAUGDP under unoptimized conditions are shown in Fig. 18, at an rms voltage of 7.5 kV and an RF frequency of 3 kHz. Clearly, the web speed required to produce the lower contact angles is too low for immediate industrial use, but we expect to see major improvements as the plasma operating conditions are optimized. In previous work on static samples, exposure times less than 1 s were routinely observed [20].

Surface treatment of PET and high-density polyethylene are being used to optimize performance. The main challenge of generating a uniform, homogenously distributed discharge was achieved with a plane-curved electrode geometry. Initial experiments show uniformity of effect on multipass treatment with no pin-holing. Plasma operating conditions need to be optimized to support higher web speeds.



Untreated PET film. ~70°

(a)

10 sec exposure to 3kHz, 9kV plasma. ~20°

(b)

Fig. 17. Digital image of water contact angle as PET film is exposed to the OAUGDP in the MOD VIII reactor. (a) Unexposed sample; (b) 10-s exposure to 3 kHz, 9-kV plasma.

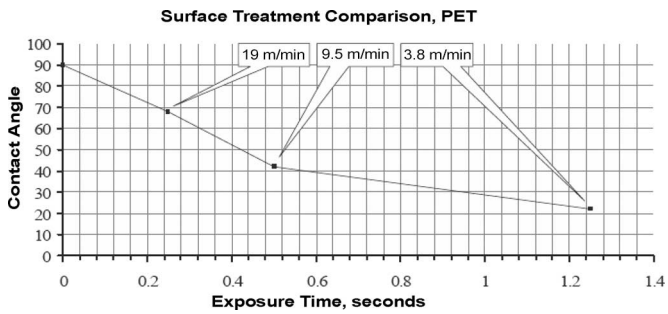


Fig. 18. PET exposed to an air plasma for various durations in the MOD VIII roll-to-roll reactor. Operating conditions: air, quartz dielectric plate, 7.5 kV, 3 kHz, and nearly 500 W of power in the plasma volume.

B. Plasma Etching Surfaces of Microelectronic Interest at One Atmosphere

In the work of Section III. A above, we demonstrated the removal of adsorbed surface monolayers of contaminants from such materials as polymers, plastics, metals, papers, fabrics, and glass [14], [19]–[30]. If the surface of these materials is exposed to the OAUGDP for minutes rather than seconds, the active species of the OAUGDP etch away the surface of the substrate after removing the surface contaminants [14]–[16], [20], [21].

1) Nanoscale Etching of Polymeric Surfaces: In the course of research aimed at increasing the surface energy of polymeric films [20], we saw evidence of vertical etching in a PET film exposed to a uniform OAUGDP operating in air. This film

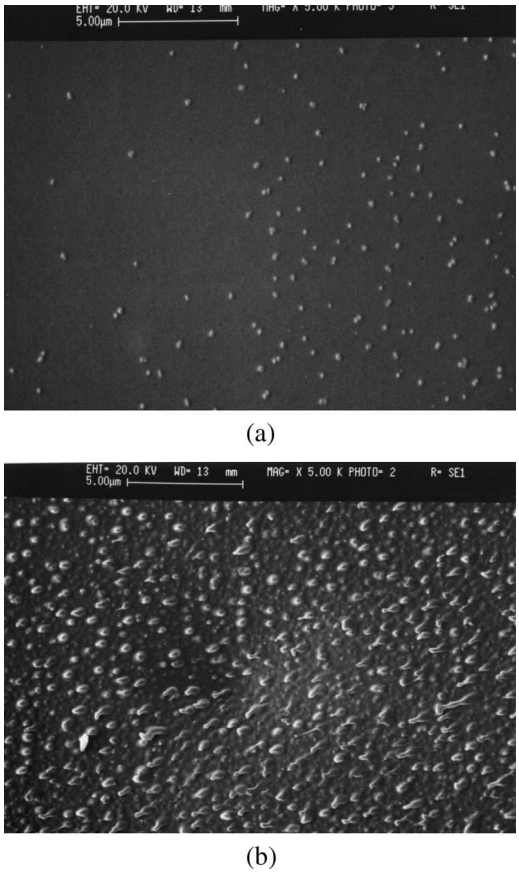


Fig. 19. SEMs of (a) untreated and (b) plasma etched PET containing scattered grains of titanium dioxide pigment. Note 5-μm fiduciary scale in the upper border. The PET was directly exposed to an OAUGDP in still air for 5 min at 5 kHz and 12-kV rms. Note the submicrometer spires under titanium dioxide grains [20].

is made commercially as the white plastic covering of baby diapers, and the white color is imparted by fine grains of titanium dioxide (TiO_2) pigment. The titanium dioxide is much harder and more resistant to etching than the PET that surrounds it, and thus serves as a mask for etching the PET under it.

Fig. 19(b) shows a SEM of a piece of the white PET film made after direct exposure for 5 min to an air OAUGDP operating in the MOD IV reactor [20] at 5 kHz and 12-kV rms, with single pass airflow. Close inspection of Fig. 19(b) reveals numerous spires that feature a grain of titanium dioxide at their top, some with diameters less than 200 nm, and length/diameter ratios as high as 20. The etching rate of PET implied by the tallest spires (those with the TiO_2 grains originally nearest the surface) over the 5-min exposure period is about 500 nm/min. There is no indication in the field of view of the SEM of pitting or melt damage similar to that in Fig. 10. It is also likely that the spire structures would have served as "lightning rods" for the formation of avalanches and filamentation, and been damaged or destroyed. The fact that no such damage is evident is another indication that the OAUGDP can be made uniform in effect.

2) Etching of Photoresist: With the assistance of the Eaton Corporation of Rockville, MD, we determined that an air OAUGDP could strip photoresist at the rate of 270 nm/min at room temperature and pressure, under relatively low-power and low-density OAUGDP operating conditions, and do so with a

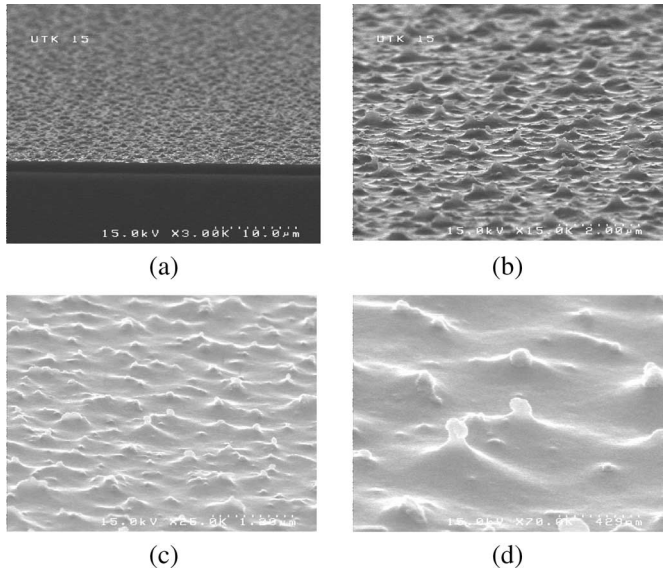


Fig. 20. "Zoom" SEM images of photoresist etched for 5 min by OAUGDP air plasma without filamentation. Lineations were produced by gas flow across wafer from upper left to lower right. Fiduciary scales are in the lower right. The total horizontal widths of the images are (a) 37, (b) 7.8, (c) 4.6, and (d) 1.7 μm. SEM images courtesy of the Eaton Corporation.

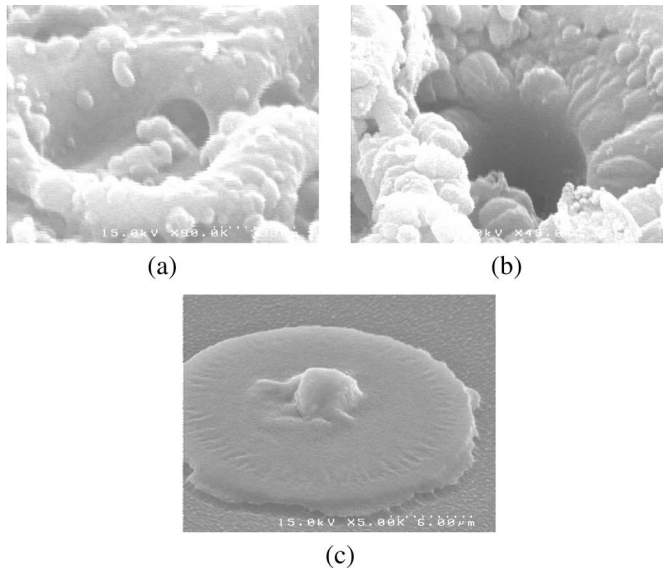


Fig. 21. SEM images of photoresist surface damage after 5-min exposure to an OAUGDP air plasma with filamentation. Fiduciary scales are in the lower right. The total horizontal widths of the images are (a) 1.2, (b) 2.3, and (c) 23 μm. SEM images courtesy of the Eaton Corporation.

uniform stripping rate variation of about 5% across the diameter (15 cm) of the etching plasma [see Section II-C2]. These results are illustrated in the topographic profile of an OAUGDP-etched photoresist coated silicon wafer in Fig. 8.

Problem areas with OAUGDP etching of microelectronic structures are evident in the SEM images of the wafer surface in Figs. 20 and 21. Fig. 20 is a series of "zoom" shots of the etched photoresist at a fractured edge of the wafer, with a silicon substrate and a layer of photoresist on top. These images feature linear structures along the gas flow direction from upper left to lower right across the wafer, and "mesas" or "spires"

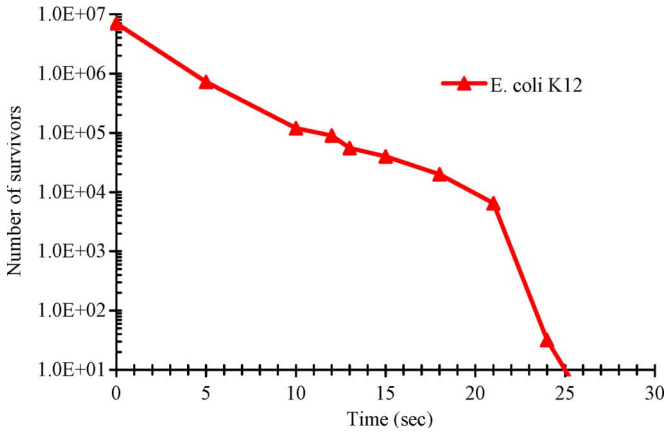


Fig. 22. Characteristic survival curve for a PP sample containing 6×10^6 *E. coli* cells directly exposed for the times shown to an air plasma in the OAUGDP reactor at conditions 10-kV rms and 7 kHz.

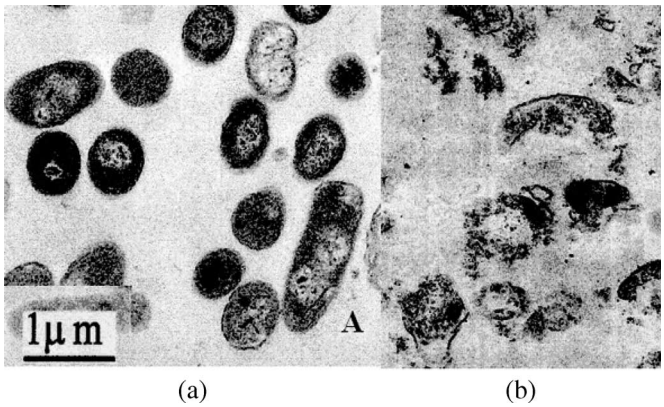


Fig. 23. SEM images of *E. coli* (a) before and (b) after 30-s exposure to the OAUGDP operating at 10-kV rms and 7.1 kHz. Note burst cell walls and release of cell contents into surrounding medium.

underneath what are presumably dust grains occasioned by the absence of clean room conditions.

Fig. 21 shows surface damage that results from operating the MOD VI reactor in the DBD/filamentary mode of operation. This takes the form of pin-holing (which, in this case, did not penetrate through the thick wafer) in Fig. 21(a) and (b), and surface melting at a filament root, in Fig. 21(c). When the reactor was operated in the uniform OAUGDP mode, as it was in Fig. 20, such surface damage is not present.

C. Sterilizing Surfaces for Healthcare, Medical, and Food Processing Applications

The etching of surfaces by OAUGDP active species illustrated by Fig. 13 strongly suggests that exposure to the OAUGDP should be a powerful sterilizing agent. Clearly, if active species are capable of removing surface contaminants and etching the surface without shadowing, no microorganism on the surface should long survive conditions sufficient to etch a much more robust, crystalline, or polymeric substrate such as photoresist.

In June 1995, a research program was initiated to determine whether exposure to the OAUGDP was effective in sterilizing and decontaminating fabrics and other surfaces. Preliminary results [31]–[35] with an air plasma were promising, and led to contracts with the National Institutes of Health, the Environmental Protection Agency (EPA), and the Department of Defense to further develop the technology. In the year 2000, this technology advanced to the point [36]–[39] that a spin-off company [Atmospheric Glow Technologies (AGT)] was formed.[1]

Prior to the formation of AGT, research at the UT Plasma Sciences Laboratory demonstrated the complete sterilization at room temperature of samples contaminated with as many as 100 million microorganisms in times ranging from 5 s to 5 min [31]–[39]. Samples exposed in the MOD VI reactor of Fig. 7 consisted of fabrics, solid surfaces, agar medium, and filter paper. A characteristic example of such data are shown in the *E. Coli* survival curve of Fig. 22. The first 20 s of exposure showed the expected exponential decrease due to chemical/environmental stress on the microorganisms by active species of the plasma. At 20 s, however, there is a knee in the curve, after which the numbers of microorganisms dropped rapidly to zero as the result of rupture of the cell wall, as is clearly indicated in the SEM images in Fig. 23. This cellular destruction assures that there will be no survivors with strong resistance to the sterilizing agent to carry this characteristic to future generations.

Sterilization was observed using air as the working gas in an OAUGDP; for direct and remote exposure of samples to the plasma; for sealed spore and sample strips; and for samples in sealed medical sterilization bags. The killing mechanism is believed to be toxic stress due to OAUGDP active species during the first phase of the survival curve, followed by structural damage to the cell walls during the latter phase of exposure (shown in the SEM image in Fig. 23). The increase in sample temperature due to direct OAUGDP exposure seldom exceeded 20 °C, which eliminated thermal stress as a significant killing mechanism. The active species most responsible for sterilization and decontamination appears to be atomic oxygen, which has a very high chemical rate constant for oxidation reactions at room temperature, and one of the smallest atomic radii of any element in the periodic table. This latter characteristic allows atomic oxygen to diffuse rapidly through biofilms or other membranes, and to travel through small crevices to reach contaminants or microorganisms.

We have exposed more than a dozen microorganisms to the OAUGDP; all have been killed in a few tens of seconds and at room temperature. We have sterilized bacteria, fungi, spores, and viruslike agents. We also have sterilized microorganisms that are "index microorganisms" for the health care and food processing industries. Some of these have an extraordinary ability to resist ionizing radiation, high temperatures, or desiccation [36]. Our survival curves characteristically have the biphasic structure illustrated in Fig. 22: a first, shallow slope due to normal stress of the OAUGDP active species, and a second much steeper phase associated with atomic oxygen-induced physical damage. Photomicrographs (such as Fig. 23) and spectroscopic measures of lipid leakage confirm massive

[1]http://www.atmosphericglow.com.

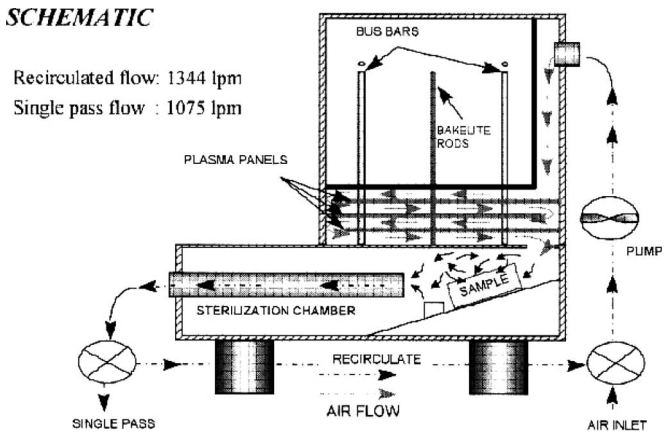


Fig. 24. Schematic of the MOD V OAUGDP remote exposure reactor with recirculating gas flow capability.

Fig. 25. Five energized plasma panels in the MOD V remote exposure reactor operating with an air OAUGDP.

physical damage to the microorganisms in the second phase of the survival curve: there are no survivors.

D. Decontaminating Surfaces Compromised by Chemical and Biological Warfare Agents

The UT Plasma Sciences Laboratory has worked on several contracts that address the use of the OAUGDP for the decontamination of surfaces compromised by (simulants of) chemical and biological warfare agents [42], [43]. Oil of wintergreen, a chemically stable simulant of chemical warfare agents, has been oxidized and denatured by 5-min of exposure to the OAUGDP. Since oil of wintergreen is inert to ozone exposure, atomic oxygen is the only active species likely to produce this and other effects (i.e., sterilization). A wide range of biological warfare simulant microorganisms have been killed at room temperature and within a few tens of seconds on a variety of surfaces, including glass, metals, fabrics, and microorganisms imbedded in agar [36].

Since the decontamination of surfaces must be done by remote exposure [42], the MOD V remote exposure reactor shown in Fig. 24 was developed. In it, an air OAUGDP plasma is created on flat panels, as illustrated in Fig. 25, and the active species produced are entrained in a serpentine gas flow that exits the plasma generating volume and passes over a workpiece in the remote exposure chamber below. The gas flow, with its

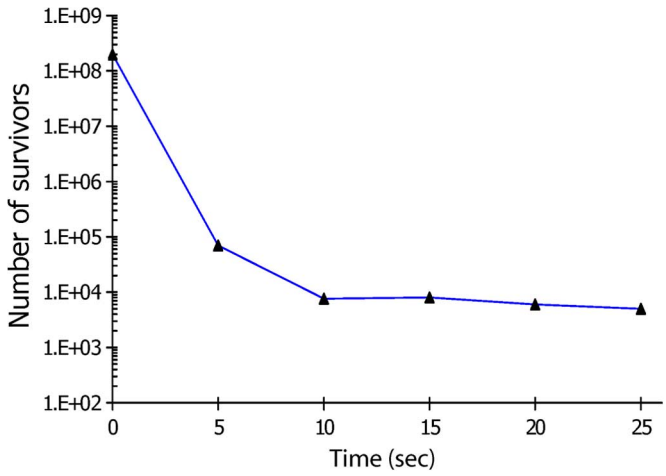


Fig. 26. Destruction of remotely exposed *E. coli* in the MOD V remote exposure reactor.

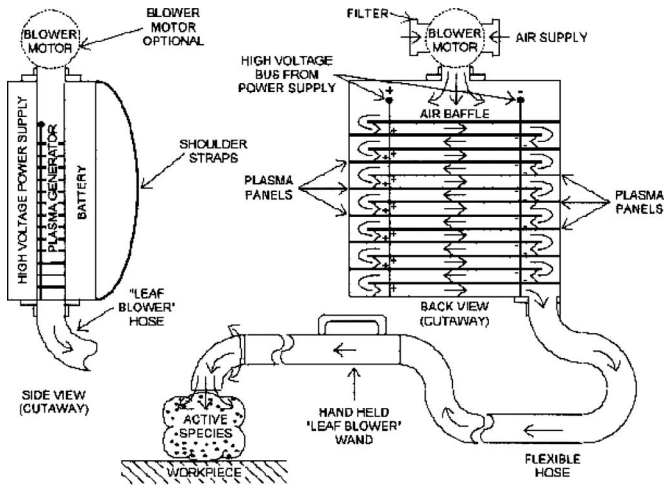


Fig. 27. Portable backpack decontamination wand based on OAUGDP active species generated by panels or between parallel plates.

entrained active species, can either be directed on a surface to be decontaminated, or recirculated to build up concentrations to treat a workpiece in the remote exposure chamber. The MOD V reactor, operating with an air plasma, can reduce the number of microorganisms by a factor of one million (i.e., achieve sterilization) after a few tens of seconds of exposure [37], [41], [42].

In Fig. 25, a digital image of five energized panels of the MOD V remote exposure reactor in operation is shown. Plasma was created on both sides of each of the panels to increase the active species entrained in the air flow. In Fig. 26, the result of a test of the MOD V reactor with a remotely placed sample of *E. coli* is shown [37].

A modification of the MOD V reactor of Fig. 24 designed to decontaminate large surface areas is a leaf-blower backpack unit like that shown in Fig. 27. In such a unit, the active species of air can be generated either on flat panels or in parallel plate discharges, either in the backpack or in the application wand itself. The latter approach may be desirable if the active species recombine or become less potent as they leave the plasma volume.

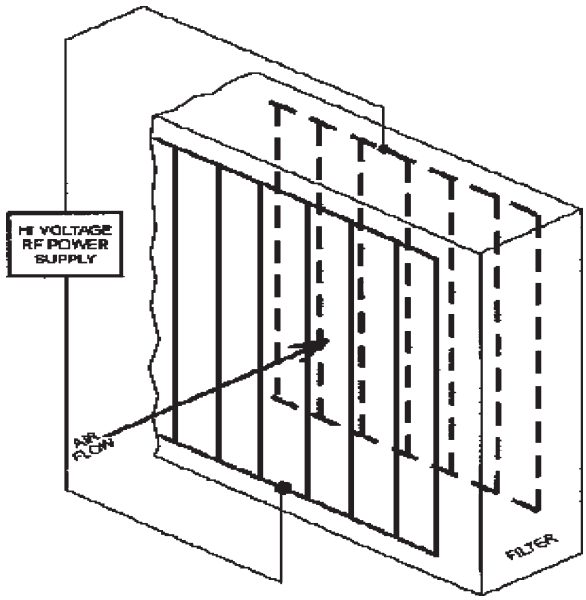


Fig. 28. Three-dimensional schematic of the sterilizable OAUGDP air filter that received a 2002 R&D 100 award.

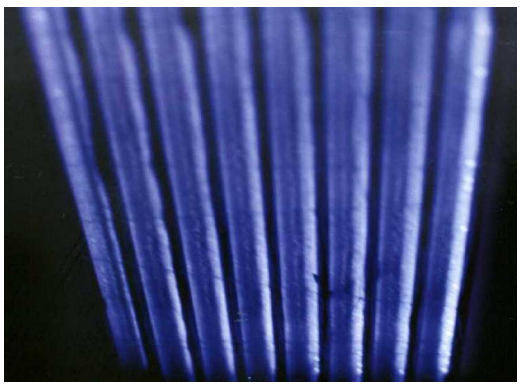


Fig. 29. Energized OAUGDP on sterilizable air filter.

E. Sterilizable Air Filter for Sick Building Syndrome

Another decontamination technology using the OAUGDP is the sterilizable air filter test assembly shown in Fig. 28 [44]–[46]. This filter utilizes a constant dc electric field across the filter material to greatly enhance its filtration efficiency. When viruses or other microorganisms are filtered from the airstream, an OAUGDP plasma is generated by energizing the electrodes on either side of the filter, to form a surface plasma [44]–[46]. The plasma active species decontaminate the filter after a few tens of seconds of exposure, and this needs to be repeated only once every 24 hr. In this way, harmful microorganisms can be filtered out of HVAC systems, and the "sick building syndrome" prevented. This sterilizable air filter received an R&D 100 award in 2002.

In Fig. 29, a digital image of the energized sterilizable OAUGDP air filter is shown. When not being sterilized in this way, the plasma is turned OFF, and a dc electric field applied between the electrodes on opposite sides of the filter to enhance its filtration efficiency.

This filter was tested in the MOD VII filtration test assembly shown in Fig. 30 [44]–[46], in which a nebulized mist containing microorganisms was carried with the gas stream through the filter material. As a paired comparison, half the filter was fitted for OAUGDP sterilization, and half was operated as a standard filter.

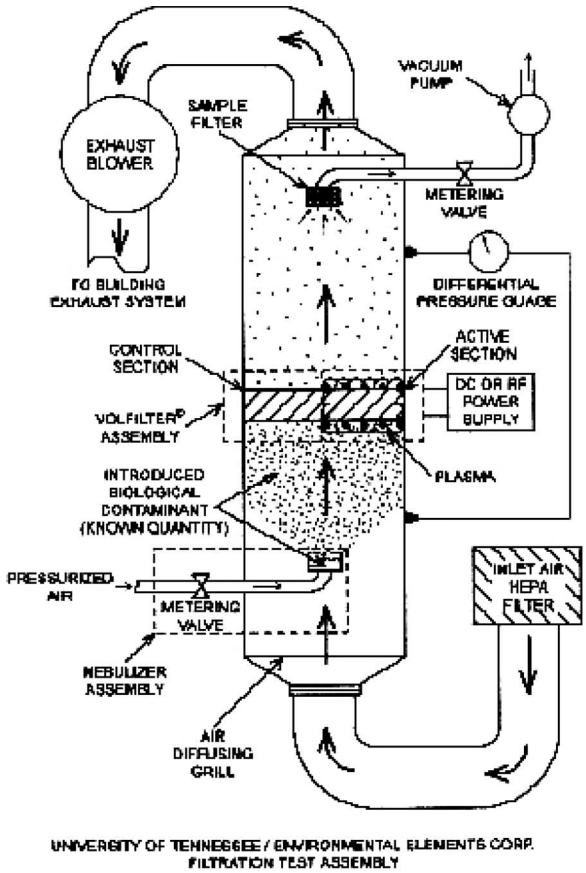


Fig. 30. Experimental arrangement of MOD VII reactor for testing of sterilizable air filter with controlled doses of microorganisms.

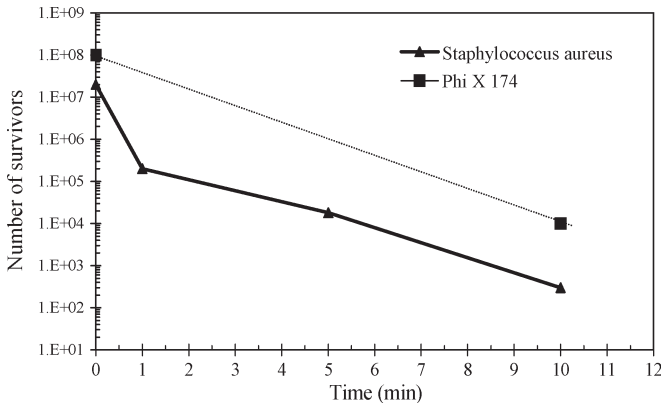


Fig. 31. Early survival curve data of *Staphylococcus aureus* and the viral bacteriophage Phi X 174 exposed to the OAUGDP active species on the sterilizable filter for the times on the abscissa.

An example of early, unoptimized data from this sterilizable air filter is shown in Fig. 31. The *S. aureus* and PhiX 174 (a viruslike bacteriophage) were individually introduced into the air stream by a nebulizer, filtered out, and then the OAUGDP energized for the times noted on the abscissa. After optimizing the plasma operating parameters, the time required

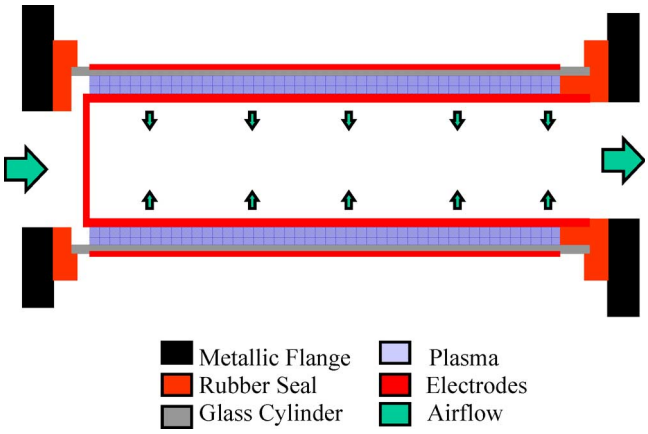


Fig. 32. Schematic of Diesel soot filter based on oxidation of soot in the engine exhaust by active species from an annular OAUGDP.

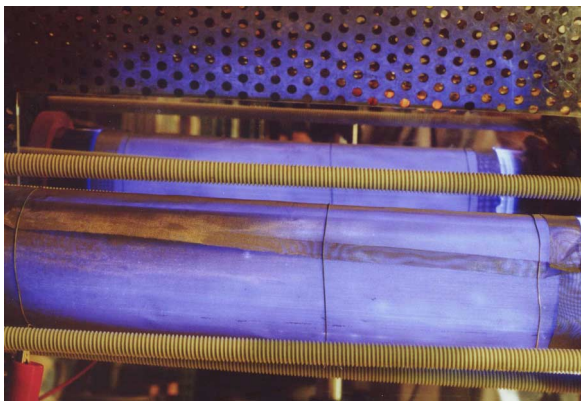


Fig. 33. Diesel soot filter in operation (angled mirror behind filter assembly).

to achieve a million-fold reduction in the number of microorganisms was reduced to tens of seconds of exposure [45].

F. Removal of Soot and VOCs From Diesel Engine Exhaust

It has been found that the fine particles of soot emitted from Diesel engines are a serious threat to public health. As a result, the EPA mandated large future reductions in such emissions. Removing such particles in an economically practicable way is difficult. Simply filtering the exhaust leads to rapid (on the order of tens of minutes) clogging of the filter by soot particles, and a need for filter replacement.

The OAUGDP soot filter shown schematically in Fig. 32 was developed at the UT Plasma Sciences Laboratory. This device requires no more than a few hundred watts of RF power, and consists of an annular OAUGDP surrounding an annular ceramic or metallic screen filter. Soot removed from the air stream is oxidized by active species from the plasma at least as fast as it accumulates on the filter surface. The volatile carbon oxides leave the device through the inner filter with the remainder of the combustion products. A digital image of this filter in operation is shown as Fig. 33.

The performance of this filter when connected to the exhaust of a 2-kW Diesel electric generator is plotted in Fig. 34, which shows the pressure drop across the filter as a function of time. When the plasma is ON, the trapped soot is oxidized and the

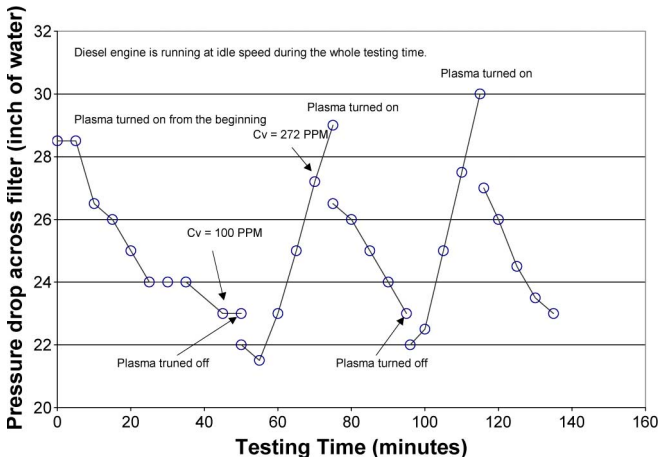


Fig. 34. Pressure drop across filter with OAUGDP off and on. The concentration of VOCs was monitored and decreases when the OAUGDP is energized.

pressure drop decreases; when the plasma is turned OFF, the soot accumulates in the filter and the pressure drop increases. The concentration of VOCs were also monitored and, as a bonus, were decreased by a factor of approximately three times when the OAUGDP was energized [14].

G. Mercury-Free Atmospheric Pressure Fluorescent Lamp

The mercury used in conventional fluorescent lamps is a serious contaminant of landfills and groundwater. The EPA therefore has encouraged the development of lighting devices as efficient as conventional fluorescent lamps, but without the mercury conventionally needed to provide UV radiation to excite their phosphors.

A fluorescent lamp based on the OAUGDP was developed at the UT Plasma Sciences Laboratory that requires neither a vacuum nor the use of mercury. This lamp consists of an OAUGDP surface layer on the outside of a cylinder or on a flat panel [49], [50]. The electrodes and surface of the OAUGDP lamp can be covered with the same phosphors used in the interior of ordinary fluorescent lamps. These phosphors are excited by the ultraviolet radiation from the OAUGDP layer above it, and emit visible radiation in a manner similar to that of a conventional fluorescent lamp.

The surface layer of OAUGDP can be generated by a flat panel [51] or, as shown in Fig. 35, by a pair of parallel wires wrapped around a cylinder, each connected to one polarity of the RF voltage. When energized, a surface plasma is generated, as is illustrated with helium in Fig. 36(a). When the wires are covered with a standard proprietary phosphor, the UV emission from the OAUGDP excites the phosphor below it, as shown in Fig. 36(b), yielding the higher level of illumination evident at the bottom of the image.

H. EHD Plasma Actuators for Subsonic Plasma Aerodynamics, Flow Acceleration, and Boundary Layer Control

The Industrial Plasma Engineering Group of the UT Plasma Sciences Laboratory has been engaged in research relevant to subsonic plasma aerodynamics and plasma actuators since

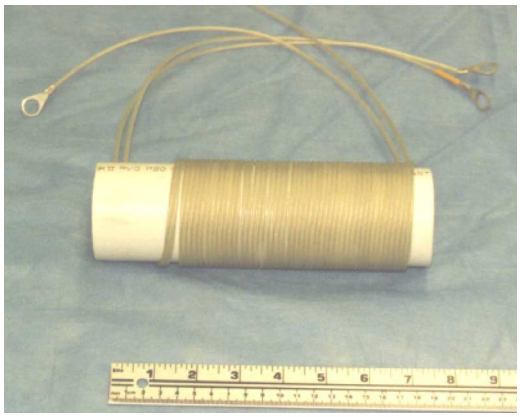
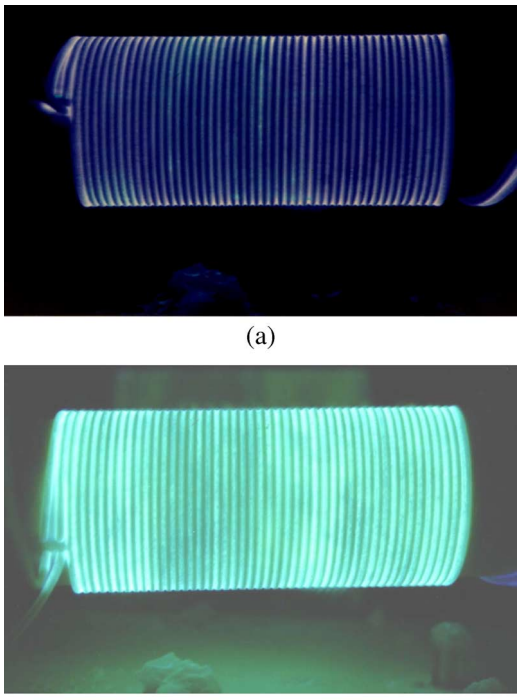


Fig. 35. Two parallel wires wound on a 5-cm-diameter polyvinyl chloride cylinder.



(a)

(b)

Fig. 36. Cylindrical plasma operating in helium gas at one atmosphere pressure. (a) No phosphors on surface. (b) With fluorescent phosphors on surface.

early 1994 [49], [50]. This research effort produced two basic patents [51], [52] and a series of papers on plasma actuators for subsonic plasma aerodynamic applications [53]–[59].

A plasma actuator consists of two parallel electrode strips, one on each side of a dielectric panel, with a small displacement gap between them. An array of plasma actuators that accelerates neutral gas flow to the right is illustrated in Fig. 37. Each actuator acts like a wall jet that adds momentum, but not mass, to the boundary layer flow. Plasma actuators can be based upon corona discharges, DBDs, and the OAUGDP. In our research, we have emphasized the physics and phenomenology of the OAUGDP, because, as a normal glow discharge, it operates at the Stoletow point [1] where the energy cost of producing an ion–electron pair is a minimum.

An example of plasma actuators in action is shown in Fig. 38, in which a series of eight plasma actuators have been mounted

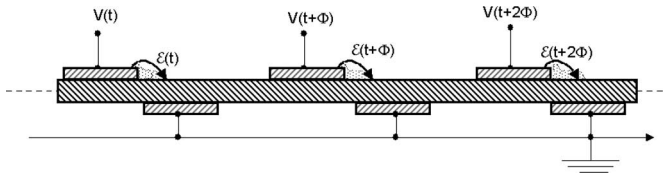
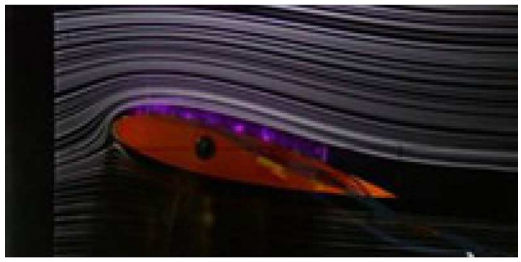


Fig. 37. Array of combined paraelectric and peristaltic plasma actuators on a flat panel that accelerate flow to the right.

(a)



(b)

Fig. 38. Flow reattachment by plasma actuators on a NACA 0015 airfoil at an angle of attack of 12°, actuator electrode voltage $V = 3.6$ kV, driving frequency $f = 4.2$ kHz, stream flow velocity 2.6 m/s. (a) Plasma actuators OFF. (b) Plasma actuators ON.

on a flexible panel attached to the upper surface of a NACA 0015 airfoil operated at an angle of attack of 12° [54], [55]. The images of Fig. 38 were taken in the NASA Langley 7 × 11 Low Speed Wind Tunnel at a free stream velocity of 2.6 m/s. These actuators add momentum, but not mass, to the flow across the airfoil from left to right. The reattachment of the flow is very evident, as is the stabilization of the instability of the separated boundary, which otherwise grows to form vortices and increase drag.

In our experiments so far, a wide range of boundary layer and flow control phenomena have been demonstrated. The boundary layer flow can be accelerated, slowed, stopped, and diverted; the boundary layer thickness can be increased or thinned; and we have seen suggestive evidence that the flow can not only be tripped into the turbulent regime by these EHD body forces, but also that the laminar regime can be extended by OAUGDP-based EHD effects [53]–[57]. As a flow control device, the OAUGDP plasma actuator can accelerate a flow and maintain a bulk velocity at least 3 cm from the surface, thus acting as a plasma pump. We have increased the drag with an OAUGDP layer in the laminar regime by a factor of at least ten, and have shown drag reductions (in the vicinity of 4 m/s free stream air flows) of up to 50% [53], [54].

Other results include demonstration of flow reattachment on the NACA 0015 airfoil illustrated in Fig. 38; and demonstration

that plasma actuators are best located at the leading edge of the airfoil, and not at the location of the flow separation bubble [55]–[57]. Thus, far, plasma actuators have produced EHD-induced flow velocities in still air of up to 10 m/s. Potential applications of EHD plasma actuators on aircraft include increasing or decreasing the lift of airfoils, increasing the stall angle of airfoils, altering the effective shape (camber) of airfoils, flow attachment for external aerodynamics on airfoils and fuselages, flow attachment for internal aerodynamics on turbine blades and ducts, and vortex suppression by active feedback control. If induced velocities of 30–60 m/s can be achieved by plasma actuators, they might be used to replace the hydraulic-mechanical control surfaces used for takeoff and landing.

IV. Discussion

Limitations of time and length have caused us to focus this paper on the OAUGDP done at the UT's Plasma Sciences Laboratory since 1988. This paper, however, is only a small part of research on atmospheric pressure plasmas and their applications that has flourished during the past twenty years. Research and development on other plasmas has been reported by Eliasson and Kogelschatz [62], who described DBDs; Schutze *et al.* [63], who described the atmospheric pressure plasma jet and compared it with other sources; Kunhardt [64], who surveyed large volume, atmospheric pressure, nonequilibrium plasmas; Napartovich [65], who also surveyed atmospheric pressure nonequilibrium plasmas, and Bogaerts *et al.* [66], who surveyed electrical discharge plasmas and their applications.

The OAUGDP originated in 1933 with the work of von Engle *et al.* [6], but the dc glow it produced was unstable to the glow-to-arc transition, and had to be started under vacuum and slowly brought up to atmospheric pressure. A parallel-plate plasma a millimeter thick was reported by Okazaki's group in Sophia University [67]–[69]. It was not clear whether this was a DBD or an OAUGDP, although a uniform appearance was reported in helium, but not in air plasmas.

A group under Massines and co-workers [11], [12], [70], [71] studied experimentally and computationally the time and space resolved behavior of helium plasmas in a parallel plate geometry, and identified the uniform mode of the discharge as having the characteristic features of the normal glow discharge during each half cycle of operation. Their work on the filamentary, delectric barrier mode of this discharge was carried over to aerodynamic plasma actuators by Enloe *et al.* [72]. Research on atmospheric plasmas that are filamentary or streamerlike has been reported by Akishev *et al.* [73] and Temmerman *et al.* [74].

V. Conclusion

Based on the exploratory studies of plasma processing applications discussed above, the atmospheric glow discharge hypothesis appears to be valid, "Any plasma processing task possible with a glow discharge in vacuum can also be performed by a glow discharge at one atmosphere, provided that long mean free paths are not required." The OAUGDP, and possibly other atmospheric plasmas, should be capable of at least as wide a range of plasma processing tasks as vacuum glow discharges, provided that long mean free paths are not required in the application. Expensive vacuum systems and batch processing are not required for OAUGDP processing, and this should open up industrial applications for which vacuum glow discharges are uneconomic.

The study of Rakowski [4] provided an example in which plasma treatment of wool under vacuum was at least a factor of ten less expensive than the conventional technology based on chemical processing, and produced none of the problematic and unwanted by-products of the conventional process. Examination of Rakowski's work shows (in Table II) that plasma treatment at one atmosphere would not need the energy input of the vacuum pumps, and would therefore be a further factor of ten less expensive than vacuum plasma processing.

Ability to operate the OAUGDP at room temperature and one atmosphere can enable applications inappropriate or impossible with vacuum glow discharges. Examples include subsonic plasma aerodynamics [49]–[59], and decontamination of large surfaces compromised by chemical or biological warfare agents [40], [43].

An unexpected outcome of this exploratory research on plasma surface treatment is that the OAUGDP is capable of directional etching at room temperature and at one atmosphere [20]. The physical processes responsible for such directional etching produce structures as small as 200 nm in diameter with height/diameter ratios as large as 20/1. This capability may lead to microelectronic and related etching applications conducted at one atmosphere. The ability to etch even photoresist can be used to also kill microorganisms, opening up many healthcare, food processing, and decontamination applications.

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J. Reece Roth (SM'71–F'81–LF'07) was born in Washington, PA, in 1937. He received the S.B. degree in physics from the Massachusetts Institute of Technology, Cambridge, in 1959 and the Ph.D. degree from Cornell University, Ithaca, NY, in 1963.

From 1963 to 1978, he was a member of the Advanced Concepts Branch of the Electromagnetic Propulsion Division of the NASA Lewis Research Center, and a Professor of electrical engineering with the University of Tennessee (UT), Knoxville, from 1978 to the present. His research interests include the physics and applications of the one atmosphere uniform glow discharge plasma (OAUGDP). He is the author of *Industrial Plasma Engineering, Volume 1: Principles* (Institute of Physics Publishing, 1995), *Industrial Plasma Engineering, Volume 2: Applications to Nonthermal Plasma Processing* (Institute of Physics Publishing, 2001), and *Industrial Plasma Engineering, Volume 3: Applications to Thermal Plasma Processing and Devices* (in press).

Dr. Roth is an Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA), and a member of the American Association for the Advancement of Science, the American Nuclear Society, the Materials Research Society, the American Society for Engineering Education, and Sigma Xi.

Sirous Nourgostar (S'05) was born in Tehran, Iran, in 1976. He received the M.Sc. degree in atomic and molecular physics from Shahid Beheshti University, Tehran, Iran. From October 2003 to August 2005, he was working toward the Ph.D. degree at the Department of Advanced Energy Engineering Science, Kyushu University, Fukuoka, Japan. Since 2005, he has been working toward the Ph.D. degree at the Department of Electrical and Computer Engineering, Knoxville, TN.

He is currently a Graduate Research Assistant with the Plasma Sciences Laboratory, UT, Knoxville, pursuing his research under Prof. J. R. Roth. His research interests include the physics and application of the OAUGDP, plasma chemical vapor deposition in atmospheric pressure and plasma propulsion as well as plasma diagnostics.

Mr. Nourgostar is a member of the American Institute of Aeronautics and Astronautics.

Truman A. Bonds (S'04) was born in Maryville, TN, in 1976. He graduated from Heritage High School in 1994, and received the B.S. degree in electrical and computer engineering from the University of Tennessee (UT), Knoxville, in 2000 and the M.S. degree, also from UT Knoxville, in August 2006. He is currently working toward the Ph.D. degree at UT.

He held a Research Assistantship with the UT Plasma Sciences Laboratory in the Electrical and Computer Engineering Department from the fall of 2004 to the summer of 2006. He holds an internship with Atmospheric Glow Technologies, Knoxville, where he conducts research in plasma aerodynamics.