Antimicrobial Plasma-Activated Water Aynergizes with UV A photons

David B. Graves, Douglas S. Clark, Matt Pavlovich, and Yuki Sakiyama

University of California, Berkeley, California

graves@berkeley.edu, clark@berkeley.edu, mattpavlovich@gmail.com, yukinori.sakiyama@gmail.com

Previous research showed that when water is exposed to air adjacent to dielectric-barrier-discharge generated plasma, various chemical compounds including hydrogen peroxides and nitrites arise in the water that kill bacteria. This water is known as Plasma-Activated Water (PAW). We showed PAW remains antibacterial for up to seven days. Suspensions of *E. coli* bacteria were exposed to PAW for various durations over a 7-day period; samples exposed for longer times showed a significant decrease in the *E. coli* population. Because of its anti-bacterial capacity, PAW has the potential for a multitude of applications such as sterilization of medical equipment and the treatment of wounds. [1]

However, the antimicrobial kinetics of PAW is fairly slow – typically tens of minutes. Also, PAW by itself requires a fairly acidic solution to be antibacterial; pH below 3 is most effective. We were interested to determine if it is possible to accelerate the antibacterial effects by adding UV photons and if the effect could be achieved in water at pH 7.

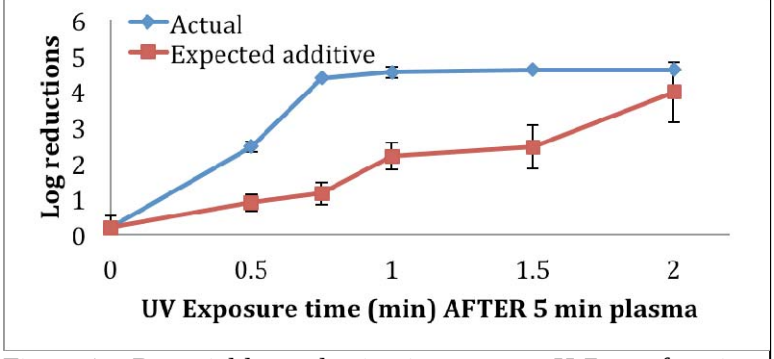


Figure 1 – Bacterial log reduction in water at pH 7 as a function of UV exposure time following 5 min plasma exposure.

It is known that UV C (e.g. 254 nm) light will directly inactivate bacteria in water; this is a widely used method to disinfect water. However, UV C photon sources usually employ Hg-containing gases in a low-pressure plasma discharge. Recent advances in light emitting diode technology allow low cost, high intensity UV A sources (315-400 nm). UV A has not been utilized extensively for antibacterial applications, but it is known from atmospheric and environmental studies that UV A photolysis of NO_2^- in solution will create NO and OH. PAW creates nitrite in solution, as noted above, so we hypothesized that UV A exposure after plasma exposure would create even more antibacterial compounds, thus speeding up disinfection.

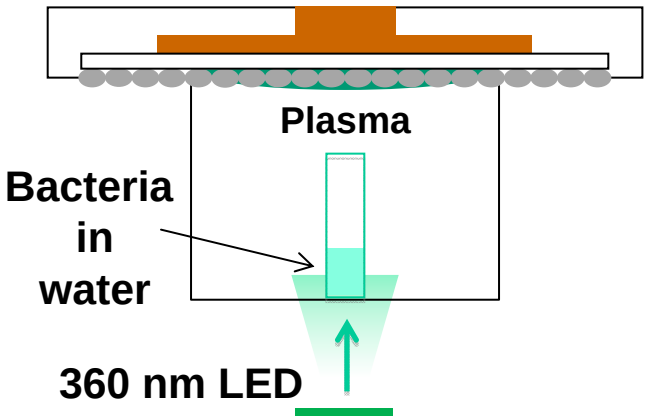
We exposed buffered (pH 7) water containing *E. coli* to air dielectric barrier discharges for 5 minutes, followed by various times of UV A exposure at ~1 W/cm^2. Plasma exposure alone and UV A exposure alone were also conducted. By adding the two isolated exposure rates (plasma alone + UV A alone = 'expected additive'), we determined that the combined exposure (plasma followed by UV A) was much more effective, demonstrating synergy, as illustrated in Fig. 1. Work is in progress to confirm and quantify this interesting and potentially useful effect.

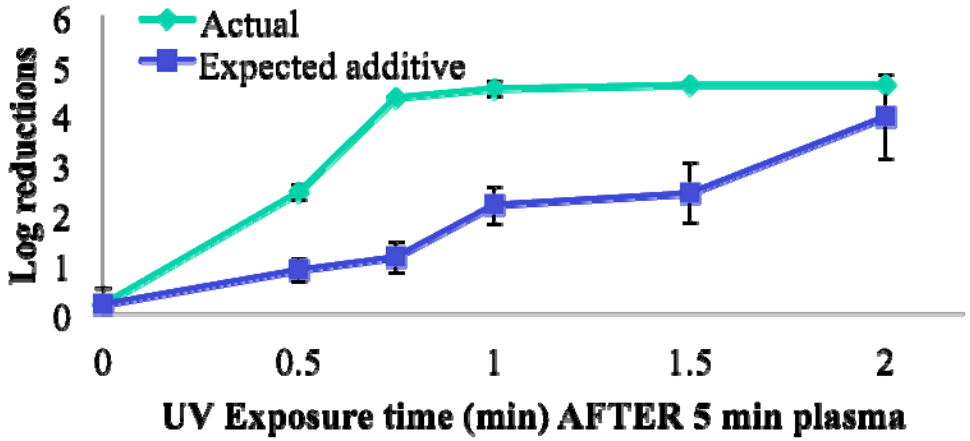
References

[1] Matthew J Traylor *et al.*, J. Phys. D: Appl. Phys. **44** 472001 (2011).

ANTIMICROBIAL PLASMA-ACTIVATED WATER SYNERGIZES WITH UV A PHOTONS

- Air plasmas interacting with water ('plasma-activated water', or PAW) create antibacterial compounds, creating a useful disinfectant for up to seven days, and a potential improvement over traditional heat and chemical methods for sterilization of medical equipment and wounds.
- Recent results show that combining PAW with UV A photons (360 nm) results in much faster antibacterial action than using PAW and UV A individually.
- Plasma-photon synergy is probably due to UV A photolysis of plasma-generated nitrite (NO_2^-), creating NO (nitric oxide) and OH (hydroxyl radical), both of which are strongly antimicrobial.





HIGHLIGHT

Center for Predictive Control of Plasma Kinetics: Multi-Phase and Bounded Systems

DOE Plasma Science Center
Control of Plasma Kinetics

Control of Ion Energy Distributions Using the Electrical Asymmetry Effect

Paola Diomede, Demetre J. Economou[(a)], and Vincent M. Donnelly[(b)]
University of Houston (a) economou@uh.edu (b) vmdonnelly@uh.edu

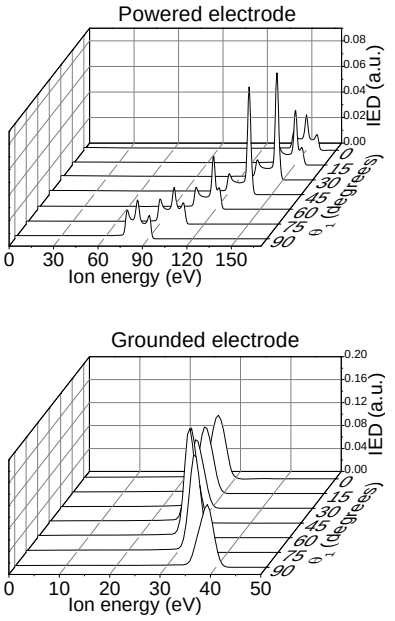


Figure 1 - Simulated IEDs on the powered (top) and grounded (bottom) electrodes of a parallel-plate CCP as the phase angle θ_1 varies (0 to 90 degrees).

Control of the ion energy distribution (IED) incident onto plasma electrodes is of critical importance in plasma etching and deposition. The ion energy must be high enough to drive anisotropic etching, but not too high to cause loss of selectivity or device damage. Several methods have been proposed to control the IED, including application of tailored voltage waveforms on the substrate electrode in cw plasmas, or application of synchronous bias on a "boundary electrode" during a specified time window in the afterglow of pulsed plasma [1]. In addition to controlling the IED, independent control of the ion flux is of paramount importance. This is very difficult to achieve in capacitively coupled plasmas (CCP) that are widely used in industrial applications. In conventional single frequency CCPs, for example, as power is increased, both ion flux and ion energy increase simultaneously. Two frequency CCPs were developed to address this issue. However, it is still difficult to substantially separate ion energy and flux, especially in geometrically symmetric reactors. In this work, a new concept, the electrical asymmetry effect [2] (EAE), was applied to control the IED. It turns out that the EAE can also provide independent control of the ion flux. In EAE, a voltage is applied to the powered electrode (where $f_2=2f_1$),

By varying the phase angle θ_1, an electrical asymmetry is generated *even in geometrically symmetric reactors*. This results in a DC bias which is controlled by varying θ_1, thereby allowing control of the IED. Here we show a case of EAE using a rapid simulation approach [3], based on an equivalent circuit model of the reactor. Conditions were as follows: Ar plasma (7.5 mTorr), $U_1=U_2=100$ V, $f_1=13.56$ MHz, $n_e=2\times10^9$ cm^{-3}, $T_e=3$ eV, and electrode area ratio =2.0 (grounded to powered electrode). Simulated IEDs on the powered (top) and the grounded (bottom) electrodes are shown in Fig. 1. The most important result is that the ion energy can be controlled simply by varying the phase angle θ_1 from 0 to 90 degrees. Also important is the fact that the ion flux to the grounded electrode is nearly constant (not shown) as the IED is shifted. The simulation predictions shown in Fig. 1 were in reasonable agreement with published experimental data [2].

References

[1]. H. Shin et al., *Plasma Sources Sci. Technol*., **20**, 055001 (2011).
[2]. U. Czarnetzki et al., *Plasma Sources Sci. Technol*., **20**, 024010 (2011).
[3]. P. Diomede, D. J. Economou and V. M. Donnelly, *J. Appl. Phys*., **111**, 123306 (2012).

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Highlight

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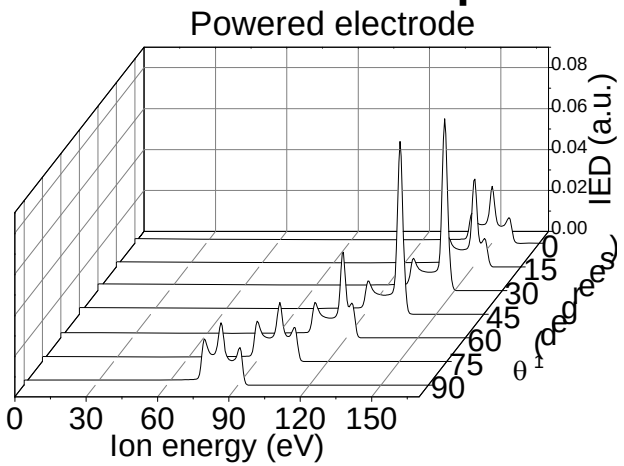
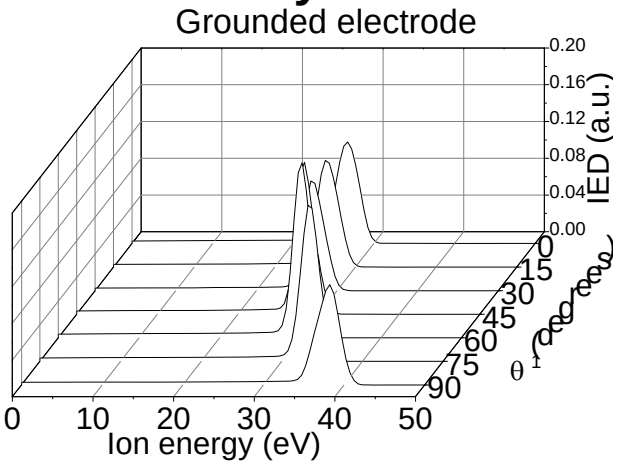
CONTROL OF ION ENERGY DISTRIBUTIONS USING THE ELECTRICAL ASYMMETRY EFFECT

- **The Electrical Asymmetry Effect (EAE) provides a new method to control the ion energy distribution (IED) on plasma electrodes. Importantly, the ion flux can also be controlled, independently of the ion energy.**
- **A voltage of the form $V(t) = U_1 \cos(2\pi f_1 t + \theta_1) + U_2 \cos(2\pi f_2 t)$ is applied to an electrode of a capacitively-coupled plasma (CCP) reactor, with $f_2=2f_1$. The DC bias (thus the ion energy) can be varied by changing the phase θ_1. A DC bias can be imposed even on a geometrically symmetric system (equal electrode areas).**
- **A rapid simulation, using an equivalent circuit model of the CCP, was used to study the EAE. Simulation predictions agreed reasonably well with data.**



Simulated IEDs on the powered electrode in a 7.5 mTorr Ar CCP. $U_1=U_2$=100 V, f_1=13.56 MHz, n_e=2 x10^9 cm^{-3}, T_e=3 eV, and electrode area ratio =2.0.



Corresponding IEDs on the grounded electrode.

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