Nanosecond-Pulsed Uniform Dielectric-Barrier Discharge

Halim Ayan, Gregory Fridman, Alexander F. Gutsol, Victor N. Vasilets, Alexander Fridman, and Gary Friedman

***Abstract*—The authors report a new nanosecond-pulsed dielectric-barrier discharge (DBD) for sterilization and other medical applications. In the literature, several discharges have been reported, with pulse durations on the order of hundreds of nanoseconds. In this paper, a novel pulsed DBD has been developed, with only few tens of nanosecond pulsewidths working uniformly over large range of electrode gap distance in air under atmospheric pressure.**

***Index Terms*—Nanosecond discharge, plasma medicine, uniform dielectric-barrier discharge (DBD).**

I. Introduction

FOR SOME period of time, the use of plasma in medicine has been limited to thermal discharges for cauterization and dissection [1]–[4]. Systems that employ afterglow from nonthermal plasma for medical treatment and disinfections have been proposed and demonstrated within the last decade [5], [6]. Although this makes it possible to work with living tissue and heat-sensitive surfaces, such treatment takes a relatively long time. It has been demonstrated recently that contact of living tissue with charges from nonthermal atmospheric-pressure plasma is much more effective for sterilization than plasma afterglow. However, nonuniform filamentary structure of usual nonthermal discharges like dielectric-barrier discharge (DBD) [7] in air and their sensitivity to gap nonuniformities pose significant challenges for medical and other applications. Filaments may produce highly localized heating and typically concentrate within areas where the gap is minimal.

A novel nonthermal nanosecond-pulsed DBD in air is demonstrated here for the first time, which does not have filamentary structure and maintains uniformity over nonuniform gap. The uniformity of this nanosecond-pulsed DBD is proven by using high-speed photosensitive film exposure. This nanosecond-pulsed DBD is also proven to be much more effective in killing bacteria on surfaces that are used as one of the DBD insulated electrodes than the conventional DBD.

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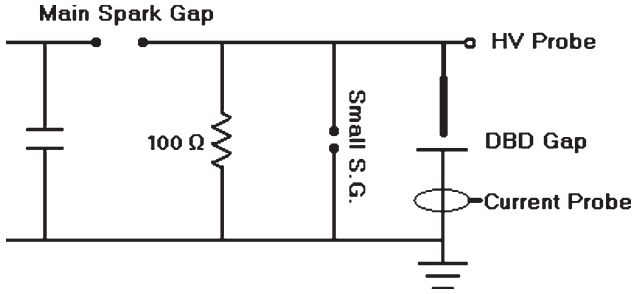


Fig. 1. Schematic of double spark-gap configuration external circuit.

Rather than using expensive and often unreliable semiconductor devices for creating nanosecond pulses [8], [9], we have developed a relatively simple double spark-gap circuit for generation of pulses with durations around 10 ns.

II. Experimental Setup

We have used sphere-to-plane discharge configuration of two DBD electrodes to demonstrate the new discharge. Dielectric-barrier-covered electrode was a glass test tube having approximately 5-mm radius of curvature and 0.75-mm thickness of glass with conductive silver paste filling inside. This test-tube electrode was in contact near its tip with the grounded plane metal electrode.

An external circuit shown in Fig. 1 has been developed with a double spark-gap configuration to obtain short pulses. When the bigger (main) spark gap breaks down, charge that is initially stored in the main capacitor is transferred to the discharge as the voltage across the plasma electrodes rises rapidly. The smaller (secondary) spark gap starts to charge and eventually short outs the DBD, resulting in a rapid decay of the voltage across the DBD electrodes.

Electrical analyses have been done by measuring instantaneous current and voltage in the plasma gap using high-speed high-voltage probe (PVM-4, North Star High Voltage, AZ) and high-speed current probe (Model #4100, Pearson Electronics, CA). The data have been recorded by using high-speed oscilloscope (TDS5052B, Tektronix, Inc., TX). A typical oscillogram of the discharge is shown in Fig. 2.

The size of the main spark gap determines the voltage that appears across the discharge electrodes after the spark breakdown. The fre‘uency of voltage pulses is determined by the magnitude of the current used to charge the main capacitor. Secondary spark gap affects mainly the length of the voltage pulse that is maintained across the DBD electrodes. For the

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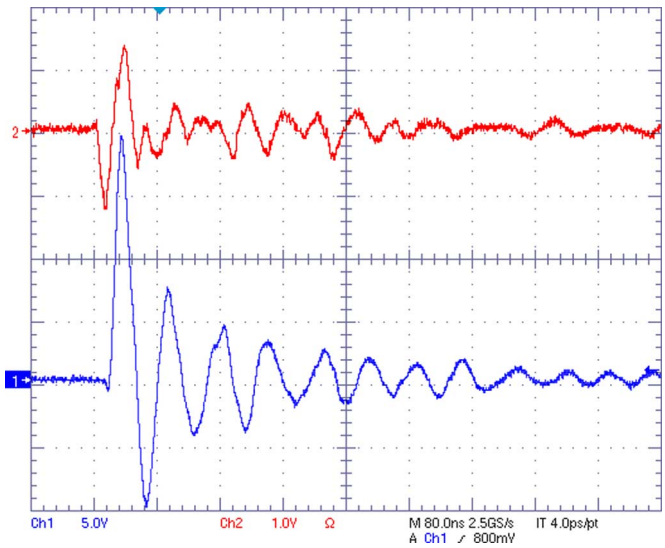


Fig. 2. Oscillogram of typical voltage (Ch1) and current (Ch2) signals ($V_{\max}$: 20 kV; pulsewidth: 20 ns).

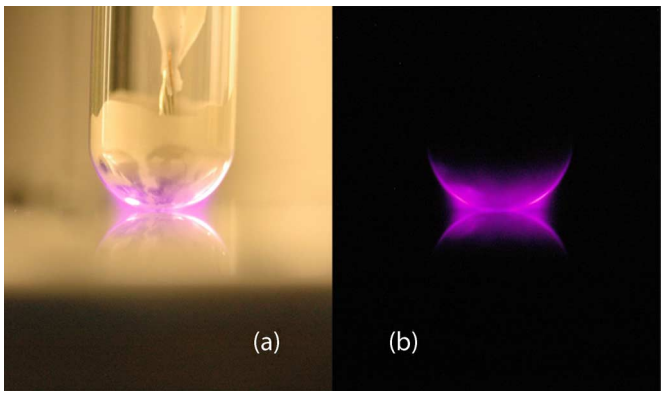


Fig. 3. Side view of nanosecond-pulsed DBD between glass-covered electrode and ground metal electrode (a) in light room and (b) in completely dark room for same exposure time (bottom halves of the images are due to reflection from the ground plate electrode surface).

current source used here to charge the main capacitor, changing the main spark gap from 15 to 24 mm with 3-mm intervals, we get repetition rates between 250 and 100 Hz, respectively, for secondary spark gap between 2.5 and 4.5 mm. Pulse duration is linearly dependent on secondary spark-gap length. For 2.5- and 4.5-mm gap distances, pulse durations are approximately 15 and 30 ns, respectively. Peak voltage across the DBD is linearly dependent on the main spark-gap distance, with approximately 1 kV/1 mm for the aforementioned range. As gap increases from 15 to 27 mm, peak voltage increases from 15 to 27 kV. The rise time of approximately 3 kV/ns is obtained on the front end of the voltage pulse.

III. Results

The discharge at the glass test-tube electrode is shown in Fig. 3. The discharge typically appears dim. Nevertheless, it can be seen in Fig. 3(a) and (b) that plasma is spread all over the spherical tip of the electrode. Fig. 3(a) was taken in light room, whereas Fig. 3(b) was taken in completely dark room. Both images were taken at the same conditions, i.e., repetition rate was approximately 190 Hz, and exposure time of the photography was 0.62 s.

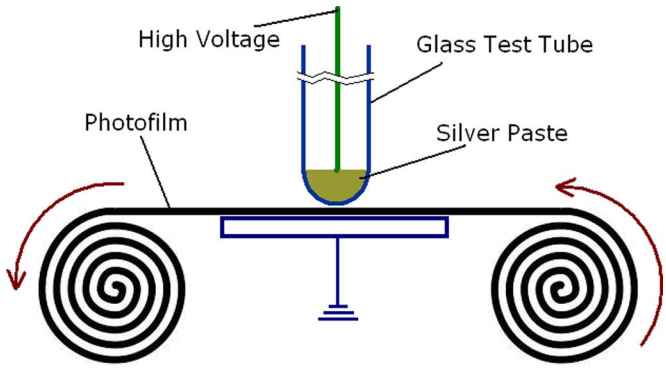


Fig. 4. Schematic of experimental setup to acquire the Lichtenberg figures on photofilm.

Optical emission spectroscopy was employed to measure the vibrational and rotational temperatures of the nanosecond-pulsed uniform DBD at 375.4- and 380.4-nm lines of the second positive system of N_2. A fiber-optic bundle (Princeton Instruments—Acton, 10 fibers—200-μm core) was utilized to acquire the optical emission from the discharge and to transmit it to the spectrometer (Princeton Instruments—Acton Research, TriVista TR555 spectrometer system with PIMAX digital ICCD camera, Trenton, NJ). The spectrum of the background noise obtained for the same exposure time was subtracted from the discharge emission spectrum prior to the temperature estimation. Curve fitting of model spectra to experimental data [10], [11] for five different measurements gave rotational temperature of 313.5 $\pm$ 7.5 K and vibrational temperature of 3360 $\pm$ 50 K.

Additionally, surface temperature of the ground electrode was measured with reversible liquid-crystal temperature-indicator strips (4002B, accuracy: ± 1 °C, LCR/Hallcrest L.L.C., IL). In the presence of the discharge, the surface temperature was around 25 °C, whereas the temperature of the ground-electrode surface without the discharge was measured to be 22 °C.

We have measured uniformity of the new discharge qualitatively by exposing a commercial photofilm to the plasma [12] (Fig. 4). The photofilm was placed between the insulated test-tube electrode and the grounded metal electrode. A roll-to-roll setup driven by an electric motor was employed to advance the photofilm at the rate of about 1 m/s, whereas pulses of DBD plasma were produced. Color and black-and-white (b&w) photofilms were used. Fig. 5 shows the Lichtenberg [12], [13] figure of a single nanosecond pulse of DBD plasma on (a) b&w and (b) color photofilms.

To demonstrate the uniformity of the nanosecond-pulsed DBD developed here, we compare its Lichtenberg figures with those of a more microsecond-pulsed DBD. The details of this microsecond-pulsed DBD can be summarized as follows. It is obtained by using a peak of approximately 10 kV which rises maximally at the rate of 10 kV/μs. Voltage in this discharge is maintained for about 2–5 μs. Thus, both voltage rise and

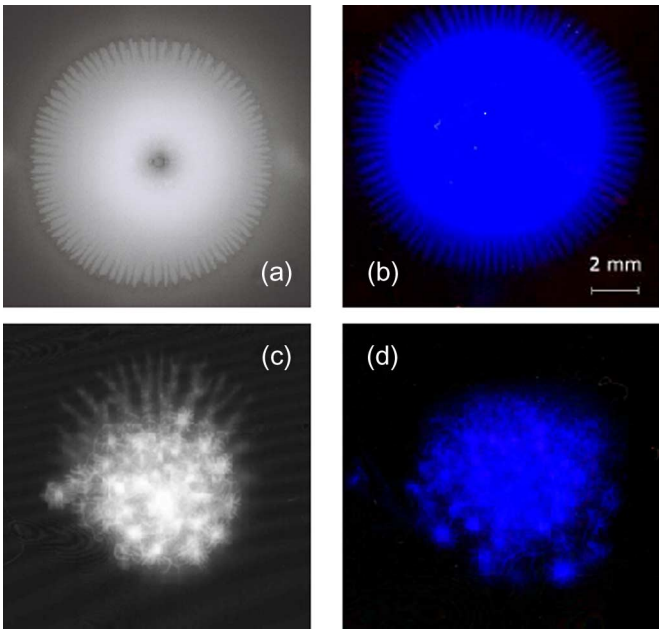


Fig. 5. Lichtenberg figures of two different DBD systems on the emulsion of the photofilms. (a) Nanosecond-pulsed DBD—b&w. (b) Nanosecond-pulsed DBD—color. (c) Microsecond-pulsed DBD—b&w. (d) Microsecond-pulsed DBD—color.

pulse duration are at least two orders of magnitude longer for the microsecond-pulsed DBD compared with the nanosecond-pulsed DBD. The microsecond-pulsed DBD was operated at 100-Hz repetition rate, its lowest repetition rate, in order to capture consecutive pulses. The Lichtenberg figures for the microsecond-pulsed DBD discussed previously are shown in Fig. 5(c) and (d). Both plasma systems were operated with the same electrode.

As shown in Fig. 5, the Lichtenberg figures show significant difference between the two discharges. The nanosecond-pulsed discharge appears in round pattern that is approximately equal in diameter to the high-voltage electrode without any bright spot or irregular pattern distribution. The contact point of the electrode appears as the dark point at the center of Fig. 5(a). Ray-type pattern at the edge of the spot appeared apparently because of the secondary surface discharge. Fig. 5(a) and (b) also shows that nanosecond-pulsed DBD ignites uniformly over a relatively large range of electrode gap distances (0.1–4 mm). It should be pointed out that test-tube electrode was in contact near its tip with the grounded plane metal electrode, and the aforementioned interelectrode gap range is due to the curvature of the glass-covered high-voltage electrode. On the other hand, discharge patterns of microsecond-pulsed DBD in Fig. 5(c) and (d) clearly show the filamentary structure (microdischarges) when used with the same electrode for the same characterization.

Power of the new nanosecond-pulsed DBD has been measured by employing calorimetry. Custom-made calorimeter setup was composed of thermally insulated housing for DBD, copper tubing welded to plane ground electrode, and inlet/outlet ports for running water. Water was pumped by a peristaltic pump (Model #3386, Control Company, TX). Steady heat transfer from discharge to the water through copper plate and

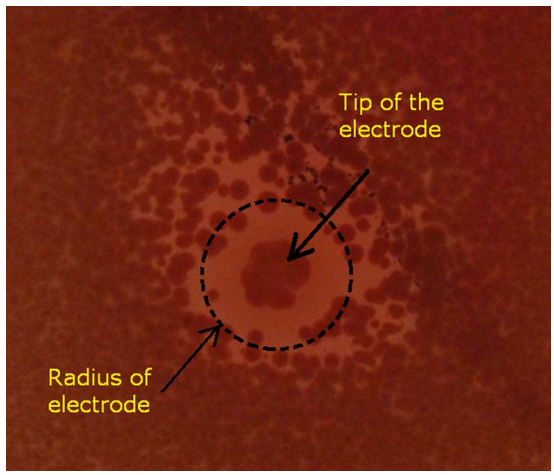


Fig. 6. Agar with skin flora treated by nanosecond-pulsed DBD ($V_{\max}$: 20 kV; repetition rate: 190 Hz).

tubing was measured at the inlet and outlet water ports with two thermometers (Model #112C, -1 °C–51 °C, 1/10 °C · div, Palmer Instruments, Inc., NC). Temperature differences between inlet and outlet were recorded periodically, and these data were fitted to two-term exponential formation curve with 95% confidence for time that goes to infinity. For this measurement, the main spark gap was adjusted to 21 mm, and the secondary spark gap was 3 mm. The average power of the nanosecond-pulsed DBD was found to be 62 ± 3 mW for these conditions. Repetition rate was measured as 192 Hz ($+20/-25$ Hz), giving 0.323 ± 0.03-mJ average energy dissipation per period. Since all of the energy dissipates during the pulse, with an average 20-ns pulse duration, the power of one single pulse can be calculated by as much as $\sim$16 kW.

Finally, nanosecond-pulsed DBD has been tested for demonstration of sterilization by treating bacteria culture on agar. Bacteria for sterilization demonstration were skin flora transferred [14] onto a blood agar plate (trypticase soy agar with 5% sheep blood; Cardinal Health, Dublin, OH). Fig. 6 shows the image of agar surface covered with skin flora (dark red area covering most of the surface) that has been sterilized (light red area) with nanosecond-pulsed-DBD treatment for 15 s. This result shows the sterilization ability of the discharge as well as its efficiency. Treatment with power as low as few tens of milliwatts for 15 s, with an average power density of approximately 1 mW/mm^2 (discharge diameter equals electrode diameter), can sterilize. This power density is one order of magnitude lower than the typical conventional DBD [15] power density. For the same duration, complete sterilization can be attained with the nanosecond-pulsed DBD with significantly lower power density.

IV. Conclusion

In summary, we have developed a new uniform nonthermal plasma system for living-tissue sterilization and other possible medical applications. Experiments reveal that new nanosecond-pulsed DBD does not require uniform discharge gaps because it can ignite and sustain over wide ranges of gap for

the same substrate, which means that it does not require smooth surface of the electrode. This feature gives an important advantage to new discharge over others, for compatibility to real tissue operations that are dominated with irregular surfaces. We have demonstrated the discharge uniformity qualitatively with a new technique for such high-frequency discharge. The Lichtenberg figures of the nanosecond-pulsed DBD show clearly that pulse durations in few tens of nanoseconds avoid streamer formation and generate uniform discharge working in atmospheric-pressure air. Additionally, we have demonstrated the ability of the discharge to sterilize. Finally, it should be emphasized that the technique that was employed to generate a few tens of nanosecond-long pulses is easy and cheap. This method would be easily used for a variety of other applications.

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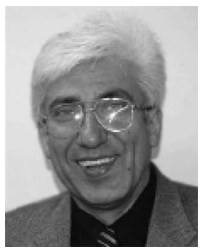
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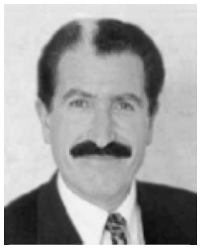
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