Discharge analysis and electrical modeling for the development of efficient dielectric barrier discharge

U N Pal, M Kumar, MS Tyagi, BL Meena, H Khatun and A K Sharma

Electron Tubes Area, Central Electronics Engineering Research Institute (CEERI)/Council of Scientific and Industrial Research (CSIR), Pilani, Rajasthan-333031, India

Email: paludit@gmail.com

Abstract. Dielectric-barrier discharges (DBDs) are characterized by the presence of at least one insulating layer in contact with the discharge between two planar or cylindrical electrodes connected to an AC/pulse power supply. The dielectric layers covering the electrodes act as current limiters and prevent the transition to an arc discharge. DBDs exist usually in filamentary mode, based on the streamer nature of the discharges. The main advantage of this type of electrical discharges is that nonequilibrium and non-thermal plasma conditions can be established at atmospheric pressure. VUV/UV sources based on DBDs are considered as promising alternatives of conventional mercury-based discharge plasmas, producing highly efficient VUV/UV radiation. The experiments have been performed using two coaxial quartz double barrier DBD tubes, which are filled with Xe/Ar at different pressures. A sinusoidal voltage up to 2.4 kV peak with frequencies from 20 to 100 kHz has been applied to the discharge electrodes for the generation of microdischarges. A stable and uniform discharge is produced in the gas gap between the dielectric barrier electrodes. By comparisons of visual images and electrical waveforms, the filamentary discharges for Ar tube while homogeneous discharge for Xe tube at the same conditions have been confirmed. The electrical modeling has been carried out to understand DBD phenomenon in variation of applied voltage waveforms. The simulated discharge characteristics have been validated by the experimental results.

1. Introduction
Dielectric barrier discharges (DBDs), also referred as silent discharges, are generated in discharge configuration with at least one dielectric barrier between two planar or cylindrical electrodes connected to an ac or pulse power supply. These dielectric layers act as a current limiter and prevent the formation of a spark or an arc discharge. DBDs are the easy way to generate non-thermal and nonequilibrium plasma at atmospheric pressure [1]. Dielectric barrier discharges are considered as promising alternatives of conventional mercury-based discharge plasmas producing highly efficient vacuum ultraviolet (VUV) and ultraviolet (UV) radiations and have found a number of industrial applications ranging from plasma display panels to surface treatment [2-4]. New application in biology and medicine are expected utilizing very mild homogeneous plasmas depending on the applications, the width of the discharge gap can range from less than 0.1 mm to about 100 mm, and applied frequency from below line frequency to several gigahertz. Typical materials used for the insulating layer are glass, quartz, ceramics, and also thin enamel or polymer coating on the electrodes. The discharge appearance of dielectric barrier discharges can be either filamentary or homogeneous, depending on experimental conditions such as discharge gas, gas pressure, gas gap, dielectric surface...
In the recent literature, many researchers have explored new efficient VUV and UV sources based on the radiation of excimer or exciplexes excited by DBDs. The efficiency of the DBD sources basically depends on the applied voltage waveform, DBD geometry, gas type and pressure, shape of electrodes etc. A quartz coaxial DBD cell filled with argon and xenon gases has been used for the experiments and discharges are characterized under different operating conditions. A stable and uniform discharge is produced in the gas gap between the dielectric barrier electrodes. By comparisons of visual images and electrical waveforms, the filamentary discharges for argon tube while homogeneous discharges for xenon tube have been confirmed. The experimental data have been used for numerically solving the circuit equations to determine discharge characteristics.

Electrical modeling and plasma simulation are the ways by which one can estimate the internal electrical and plasma parameters of the DBD cell. The internal electrical parameters (gas gap voltage, memory voltage, barrier voltage, discharge current, consumed discharge power etc) are the key parameters to analyze theoretically the efficiency of the DBD cell. The electrical modeling has been carried out to understand DBD phenomenon in variation of applied voltage waveforms and gas pressures. We have proposed a simulation model of DBD based on the equivalent electrical circuit for argon filled DBD cell. In our approach, we have compared the experimental and simulated DBD...
discharge characteristics explicitly. This model is implemented using MATLAB Simulink in which the observed discharge conditions have been included. The results obtained from the simulated model have been compared with experimental results.

2. Experimental set-up

2.1. DBD cell design
The figure 1(a) shows the picture of coaxial DBD cell filled with argon and xenon. Figure 1(b) depicts the schematic of the coaxial DBD lamp consisting of two fused quartz tubes. The outer surface of quartz tube is wrapped by copper wire mesh electrode and the inner electrode of Cusil foil has been inserted into the coaxial tube to the close proximity of inner wall. A high voltage signal is applied on the inner electrode, while the outer mesh electrode is grounded. The inner radius of outer quartz tube is 18.5 mm and the thickness is 1.5 mm, while the inner radius of inner quartz tube is 15 mm and the thickness is 2 mm. The gas gap is 1.5 mm. Total length of the argon DBD tube is 30 cm while the xenon DBD tube is 10 cm. The outer mesh and the inner foil electrode wrap 9 cm and 6 cm of the respective tubes.

2.2. Set-up
Figure 2 shows the experimental set-up. A sinusoidal high voltage supply (Huttinger HF Generator TIG 10/100 PSC) up to 2.4 kV peak with frequencies from 20 to 100 kHz has been applied to the discharge electrodes for the generation of microdischarges. The variable oscillator circuit capacitances of the generator (parallel connection of individual capacitors within a block) make it possible to change the operating frequencies and matching to the output load. The DBD cell has been mounted on ultra high vacuum pump station. It has been evacuated to $8 \times 10^{-9}$ mbar pressure and baked up to 450°C to achieve ultimate pressure of $5 \times 10^{-9}$ mbar. At room temperature, argon and Xe gases of 99.99% purity have been filled in the DBD cell. The gas flow has been controlled by mass flow controller (Matheson: 8272-0453). The pressure has been measured by pressure gauges (Leybold: 16040, Pfeiffer: PKR251) and pressure has been maintained by vacuum valves (Matheson: 316L, Varian: 9515091). The outer wire mesh electrode acts as a cathode while the inner foil electrode as an anode. The wire mesh electrode allows the radiation to come out of the tube for spectroscopic analysis. An external capacitor $C_{esc}$ (500 pF) has been used to measure transferred charges. A 1:1000 high voltage probe (Tektronix P6015A) measures the voltage across the DBD tube and Rogowski-type Pearson current monitor, Model 110 (0.1 V/A, 1 Hz - 20 MHz, 20 ns usable rise time) measures total current flowing through the DBD tube. The total current and applied voltage waveforms are visualized by means of a four-channel Tektronics TDS 3034B digital oscilloscope. The oscilloscope is interfaced with the personal computer for real time analysis and recording the voltage and current waveforms.

3. Electrical analysis and modeling

3.1. Equivalent electrical circuit
An electrical analogous circuit of Argon DBD tube is shown in figure 3 (a). The equivalent electrical model of the DBD tube consists of three capacitors in series connection. The inner and outer quartz tube forms the dielectric barrier capacitance $C_{d1}$ and $C_{d2}$ whereas the gas gap forms the capacitance $C_g$. Since $C_{d1}$ and $C_{d2}$ are in series combination, it can be represented by a single capacitance $C_d$. The equivalent capacitance has been calculated theoretically using coaxial topology of two quartz barrier. With the experimental values of voltage and current, the effect of additional capacitance $C_e$ in parallel with DBD cell has been noticed. It represents the parasitic capacitance along with cable capacitance of RF supply and additional electrical circuit components. The impedance of microdischarges is represented by $Z_d$, which is in parallel with $C_e$. Two discharges are taking place for a particular time interval during one complete cycle of applied voltage waveform [12]. The switch $S_e$ is used to act as a virtual circuit component to represent this phenomenon. The discharge plasma is represented by a
voltage controlled current source $I_{dis}(t)$. This conductive discharge current depends on the gas gap voltage $V_g(t)$. In this model $V_a(t)$, $V_{dis}(t)$, $V_{ds}(t)$, $I_{dis}(t)$, $I_{a}(t)$ and $I_{tc}(t)$ are externally excited voltage, voltage across the inner & outer dielectric barriers, displacement current through the gap,

Figure 3. (a) Equivalent electrical circuit of DBD tube, (b) Simulation model in Simulink.

displacement current through the $C_s$ and the external current, respectively. Using Kirchoff’s theorem for the circuit given in figure 3 (a), we obtained the following equations

\[ V_a(t) = V_d(t) + V_g(t) \] \hspace{1cm} (1)
\[ I_{ac}(t) = I_{a}(t) + I_{ac}(t) \] \hspace{1cm} (2)
\[ I_{dis}(t) = I_{dis}(t) + I_{d}(t) \] \hspace{1cm} (3)

Total external current through DBD $I_{dis}(t)$, and displacement current through the gap $I_{a}(t)$, can be written as

\[ I_{dis}(t) = C_d \frac{dV_a(t)}{dt} \] \hspace{1cm} (4)

Where $V_a = V_{di} + V_{d2}$ is the voltage across dielectric and $C_d = C_{d1}C_{d2}/(C_{d1}+C_{d2})$ is total capacitance of dielectric.

\[ I_{a}(t) = C_g \frac{dV_g(t)}{dt} \] \hspace{1cm} (5)

Differentiating equation (1) with respect to time and substituting (4) and (5) in (1)

\[ \frac{dV_a(t)}{dt} = \frac{1}{C_g} (I_{dis}(t) - I_{dis}(t)) + \frac{I_{a}(t)}{C_d} \] \hspace{1cm} (6)

Rearranging equation (6)

\[ I_{dis}(t) = (1 + \frac{C_g}{C_d}) I_{a}(t) - C_g \frac{dV_a(t)}{dt} \] \hspace{1cm} (7)

The dielectric barrier voltage, $V_d(t)$ and gas gap voltage, $V_g(t)$ are
\[
V_d(t) = \frac{1}{C_d} \int I_{dc}(t) dt + V_{m0}
\]
and the memory voltage for AC voltage excitation is given by
\[
V_{m0} = -\frac{1}{2C_d} \int I_{abd}(t) dt
\]

In equations (8) and (9), \(V_{m0}\) corresponds to the memory voltage, induced by charge accumulation on the dielectric barriers during previous half period. In other words, \(V_{m0}\) “memorizes” the previous discharge events. The memory voltage has different value corresponding to applied voltage waveform [13]. The number of data points for \(V_d(t)\) and \(I_{dc}(t)\) curves have been obtained by connecting the oscilloscope to the computer. These experimental values are used to solve the above equations for evaluating all the discharge characteristics.

### 3.2 Equivalent Simulink model

The simulation model made in Simulink is shown in figure 3 (b). This simulation model is based on the equivalent electrical circuit proposed in figure 3 (a), in which gas properties are not considered. Thus emphasis has been mainly laid on the electrical operating conditions of the circuit. However parameters governing ignition and extinction of microdischarges are taken into account. The effect of discharge phenomenon on the gas gap capacitance is considered, which has also been proved as efficient way of analyzing plasma impedance during discharge.

The pulse generator which derives the switch \(S_w\) is programmed according ignition and extinction discharge timings. The timing is deduced from the observed breakdown voltage and frequency of the experimental results. The switch \(S_w\), which is actually a virtual circuit component for numerical analysis of experimental data, is effectively used in this simulation to investigate the effect of impedance in discharge phenomenon. It reduces whole circuit to a purely capacitive circuit when no discharge is taking place. During discharge period, when the switch \(S_w\) is on, the plasma impedance is introduced into the circuit. The plasma impedance is comprised of capacitor \(C_{dis}\) in series with resistance \(R_{dis}\), which represents resistance of filamentary microdischarges. The capacitor \(C_{dis}\) is different from gas capacitance \(C_g\) as it varies due to change in relative permittivity of gas during ionization [14]. The controlled current source block has been modeled cautiously so that it cannot deviate from equation 7. \(R_c\) represents the resistance of the wires and connectors in the circuit, which is of the order of tens of ohms. Thus this modeling proves faster methods of analyzing discharge characteristics as compared to the long numerical calculations. The equivalent electrical modeling for optimization of xenon DBD tube will be carried out.

### 4. Results and discussion

#### 4.1 Discharge mode

In the experiment the voltage applied to the metal foil electrode and mesh electrode has been manually increased very slowly. When the applied voltage rose to certain value, \(V_{bd}\) (Breakdown voltage), discharge began with some filaments distributed on the dielectric wall, but the intensity of the visible light emitted from the discharge gap was very low. If the applied voltage is increased further, the numbers of filaments increases and finally get diffuse. Figure 4 (a) shows the average image of discharges occurring in argon filled DBD tube. The image makes sure that the diffuse discharge covers the entire surface of the electrodes. Figure 4 (b) is the total current trace together with applied voltage, where the discharge current waveform has number of current pulses with nanosecond order, which are
superimposed on the total current, confirms filamentary discharges [12]. The nature of filamentary or homogeneous discharges can also be investigated by seeing the nature of Lissajous figure. In case of filamentary discharges its Lissajous figure is drawn as a parallelogram and while in case of homogeneous discharge its Lissajous figure appears as only two voltage lines, the top line and the bottom line of the parallelogram, because the traces of the two vertical charges lines jump back and forth within so short a time of only one current pulse that they can hardly be observed. In case of xenon DBD tube, figure 5 (a) – (b) confirm the discharges to be homogeneous type.

Figure 4: DBD in argon atmosphere (P: 1000 mbar, f=45.7 kHz) (a) picture of diffused discharge, (b) applied voltage and total current waveforms.

Figure 5: DBD in xenon atmosphere (P: 700 mbar, f=35.5 kHz) (a) picture of homogeneous discharge, (b) applied voltage and total current waveforms.

Figure 6. Applied voltage and total current waveform (gas: argon at 1000 mbar, f = 45.7 kHz) (a) experimental and (b) simulated results.

4.2. Discharge characteristics
Figure 6(a) represents the applied voltage $V_a(t)$ and total current $I_{tc}(t)$ waveforms measured at 1000 mbar argon atmosphere for 45.7 kHz frequency. Figure 6(b) represents the simulated results for the same operating conditions. The amplitudes of total current for both experimental and simulated curves are same but the phases after the occurrence of discharges are different. This difference is owing to discrete time modeling of simulation model, in which the plasma impedance comes under effect for a
particular time only and decay time of this effect is nearly zero. In the present work the emphasis is mainly on overall performance of simulation in terms of amplitude & nature of discharge peaks. The dynamic behavior of different voltages for DBD cell has been calculated from theoretical equations and given in figure 7. The dielectric barrier voltage $V_d(t)$ and memory voltage $V_{m0}$ are calculated using equations (8) & (10) respectively. Discharge occurs when applied voltage reaches the breakdown voltage and results in significant electron production. After that, produced electrons move towards momentary anode driven by gap voltage and reversing the polarity of initial memory voltage, increasing its magnitude in the direction opposite to applied voltage $V_a(t)$. It is clearly evident that the gap voltage attains positive value prior to applied voltage which confirms the effect of memory voltage.

The instantaneous input power delivered by the electric supply $P_{sup}(t)$, and the power consumed $P_{dis}(t)$, during discharge are respectively

$$P_{sup}(t) = V_a(t)I_n(t)$$

$$P_{dis}(t) = V_g(t)I_{dis}(t)$$

(11)

(12)

The mean value of supplied power $\langle P_{sup} \rangle$ and consumed power $\langle P_{dis} \rangle$ are as follows

$$\langle P_{sup} \rangle = \frac{1}{T} \int_0^T P_{sup}(t)dt$$

$$\langle P_{dis} \rangle = \frac{1}{T} \int_0^T P_{dis}(t)dt$$

(13)

(14)

The electrical energy deposited in one discharge

$$W_{dep} = \frac{\langle P_{dis} \rangle}{2f}$$

(15)

The instantaneous values of the input power and the consumed power during discharge have been obtained using equations (11-12). The real power input occurs during the discharge phase. The average power supplied and consumed in the DBD cell are calculated using equation (13-14) and are found to be 15.09 W and 4.85 W respectively. The energy deposited by single discharge, $W_{dep}$ has been calculated by equation (15) and is 53µJ. This deposited energy can also be calculated by the enclosed area of Lissajous figure. The Lissajous figure of the discharge for argon DBD tube is shown in figure 8. From figure 8, the enclosed area is 44.8µJ. The theoretical calculated energy and measured energy obtained from Lissajous figure are nearly equal. With all these parameters conversion efficiency can be determined, which is found to be 32.1 %.

![Figure 7](image1)
![Figure 8](image2)

**Figure 7:** Spectroscopic measurements from xenon DBD tube

**Figure 8:** Q-V waveform for one period (gas: Argon at 1000 mbar. f=45.7 kHz).
5. Conclusion
The experiments have been performed using argon and xenon DBD tubes. The discharges are analyzed in the coaxial DBD cell filled with argon and xenon and are found to be the filamentary and homogeneous respectively. An electrical circuit has been proposed to analyze internal electrical parameters for the efficiency improvement of DBD sources. For this, equations based on the equivalent electrical circuit have been formulated. The dynamic behavior of discharge has been studied. An analogous model for the proposed electrical circuit has been implemented in the MATLAB Simulink. A good correlation has been achieved between the dynamic behavior of the discharge characteristics evaluated with the simulation model and experimental values.

Acknowledgements
This work has been carried out under CSIR Network Programme. Authors are grateful to Ms Pooja Gulati and Mr. Parvendra Kumar for their suggestions and untiring support.

Reference:
[1] Becker K H, Kogelschatz U, Schoenbach K H and Barker R J 2005 Non Equilibrium Air Plasmas at Atmospheric Pressure (Beograd: Institute of Physics)
[2] Kogelschatz U, Eliasson B and Egli W 1999 From ozone generators to flat television screens: history and future potential of dielectric-barrier discharges Pure Appl. Chem. 71 1819–28
[3] Rehn P, Wolkenhauer A, Bente M, Forster R and Viol W Dielectric barrier discharge treatments at atmospheric pressure for wood surface modification 2003 Surf. Coat. Technol. 174–175, 515–18
[4] Kunhardt E E 2000 Generation of large-volume, atmospheric pressure, nonequilibrium plasmas IEEE Trans. Plasma Sci. 28 189–200
[5] Radu I, Bartnikas R, Czeremuszkin G and Wertheimer M 2003 Diagnostics of dielectric barrier discharges in noble gases: atmospheric pressure glow and pseudoglow discharges and spatio-temporal patterns IEEE Trans. Plasma Sci. 31 411–21
[6] Reece Roth J, Rahel J, Dai X and Sherman D M 2005 The physics and phenomenology of One Atmosphere Uniform Glow Discharge Plasma (OAUGDP™) reactors for surface treatment applications. J. Phys. D: Appl. Phys. 38 555–67
[7] Rahel J and Sherman D M 2005 The transition from a filamentary dielectric barrier discharge to a diffuse barrier discharge in air at atmospheric pressure J. Phys. D: Appl. Phys. 38 547–54
[8] Gherardi N and Massines F 2001 Mechanisms controlling the transition from glow silent discharge to streamer discharge in nitrogen IEEE Trans. Plasma Sci. 29 536–44
[9] Massines F, Rabelhi A, Decomps P, Gadri R B, Segur P and Mayoux C 1998 Experimental and theoretical study of a glow discharge at atmospheric pressure controlled by dielectric barrier J. Appl. Phys. 83 2950–7
[10] Massines F, Segur P, Gherardi N, Khamphan C and Ricard A 2003 Physics and chemistry in a glow dielectric barrier discharge at atmospheric pressure: diagnostic and modeling Surf. Coat. Technol. 174–175 8–14
[11] Okazaki S, Kogoma M, Uehara M and Kimura Y 1993 Appearance of stable glow discharge in air, argon, oxygen and nitrogen at atmospheric pressure using a 50 Hz source J. Phys. D: Appl. Phys. 26 892–900
[12] Valdivia-Barrientos R, Pacheco-Sotelo V, Pacheco-Pacheco M, Benítez-Read J S and L’opez-Callejas R 2006 Analysis and electrical modeling of a cylindrical DBD configuration at different operating frequencies, Plasma Sources Sci. Technol. 15 237-245
[13] Liu S and Neiger M 2003 Electrical modeling of homogeneous dielectric barrier discharge under an arbitrary excitation voltage J. Phys. D: Appl. Phys. 36 3144–50
[14] Raizer Y P 1991 Gas Discharge Physics (Berlin: Springer) chapter 3