Simulation of Dielectric Barrier Discharge Lamp Coupled to the External Electrical Circuit

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Abstract: The present work uses COMSOL to simulate the Dielectric Barrier Discharge (DBD) lamp coupled to the external electrical circuit. The coupled system is modeled to capture the effect of the electrical parasitic elements on the efficiency of the DBD. This is a more realistic situation as compared to the previous modeling trials where it was assumed that a perfect voltage source is applied to the lamp terminals. The obtained results show that the circuit parasitic inductance causes unwanted ringing and lowers the rate of rise of the applied voltage which degrades the system performance.

Keywords: Plasma, electrical circuit parasitics, Coupled PDE-ODE system.

1. Introduction

The DBD lamp is a very attractive UV source as it produces a narrow bandwidth radiation, has longer lifetime, ignites nearly instantly and is mercury free [6].

The DBD lamp can be modeled by a system of partial differential equations (PDEs) consisting of a number of continuity equations (equaling the number of species being considered) coupled to Poisson's equation. The system of equations is solved to yield the temporal and spatial evolution of the density of particles and the electric field.

The DBD has been usually modeled by specifying a boundary condition of a certain applied voltage. However, this is realistically not possible from the electrical circuit point of view as this means that the series parasitic elements in the circuit have been neglected. It is also mentioned in patents [1-3] that the lamp efficiency is affected by the resonance caused by the interaction between the lamp capacitance and the parasitic inductance.

Therefore, we propose in this paper to couple the DBD PDE system to the ODE describing the external circuit to show the effect of the parasitics on the lamp efficiency.

2. Theory

The configuration of the symmetrical DBD lamp is shown in figure 1. As soon as the gas in the DBD lamp breaks down, the gas is transformed into plasma. To model the plasma, the spatial and temporal evolutions of the different species present in the plasma have to be modeled. One of the modeling approaches used is based on the solution of the first three moments of the Boltzmann equation representing the mass, momentum and energy continuity equations [7, 12].

Since the DBD lamp is preferably operated at high pressure, two simplifications can be utilized to reduce the number of required equations. The first simplification is to consider a drift-diffusion model for the different species instead of solving the momentum continuity equation.

The second simplification is based on the Local Field Approximation where all transport coefficients and collision frequencies are given as functions of the local electrical field therefore the energy equation is completely eliminated from the equation system. As a consequence, only the mass continuity equation is solved to describe the temporal and spatial evolution of the different species in the plasma [8, 9].

The discharge in the DBD lamp is self-extinguished due to the surface charge accumulation on the dielectric barriers. Therefore, the DBD always works under non equilibrium condition which is favorable for producing UV radiation [6].

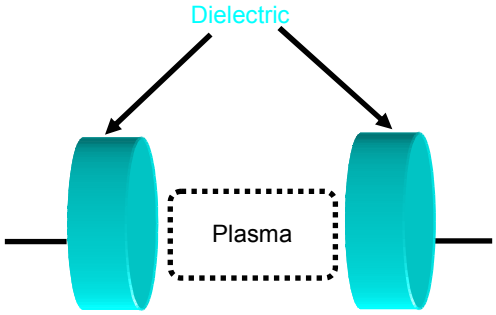

Figure 1. DBD Configuration

3. Governing Equations

The physics of the DBD can be described using a system of coupled PDEs. Each particle included in the chemical model of the gas is described by a continuity equation. The continuity equations depend on the electric field *E*. Therefore, these equations are coupled to Poisson's equation to solve for *E* and the density of the different particles. The external circuit is described by an ODE. The governing equations are:

1. Continuity equation: $\frac{\partial n_j}{\partial t} + \nabla \cdot \Gamma_j = S_j$ (1)

n_j Volume density of particle *j*

S_j Source term for the particle *j* which describes the net rate of generation of particle *j*.

Γ_j Flux of particle *j*

The continuity equations are only solved in the gas domain.

2. Poisson's equation: $\nabla \cdot \varepsilon E = \rho_v$ (2)

where $E = -\nabla V$, V is the electric potential.

ε Dielectric permittivity

ρ_v Net volume charge density

Poisson's equation is solved in the dielectric barriers and in the gas.

3. Kirchoff's Voltage Law:

The external circuit used for demonstration purposes is shown in figure 2. It is described by an ODE which is obtained from Kirchoff's voltage law (KVL).

$$v_s = R_s i_{DBD} + L_s \frac{di_{DBD}}{dt} + v_{DBD} \quad (3)$$

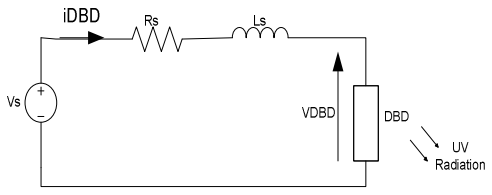

Figure 2. DBD connected to external circuit

4. Numerical Model

The numerical model that describes the DBD is based on the chemical species included in the chemical model. Figure A.1 in Appendix A shows the different species with the chemical reactions that either generate or destroy the corresponding particle. The chemical reactions determine the source term S_j in the continuity equation (1) of each particle.

The flux of particle *j* is composed of diffusion and drift components and is given by equation (4).

$$\Gamma_j = -D_j \nabla n_j + sign(q_i) n_j \mu_j E \quad (4)$$

D_j Diffusion coefficient of particle *j*

μ_j Mobility of particle *j*

q_j Charge of particle *j*

The transport coefficients are function of the electrical field as a result of the Local Field Approximation [8]. These functions are shown in figure A.4 and A.5 in Appendix A.

Regarding Poisson's equation (2) ρ_v is the net volume charge density due to electrons and positively charged ions. The volume charge is given by $\rho_v = q(n_i + n_{i2} - n_e)$, where n_e, n_i and n_{i2} are the densities of the electrons, ions and molecular ions respectively

4.1 Boundary Conditions

The boundary conditions used in this model are as follows:

a) Boundary conditions on the continuity equations:

A specific flux at both boundaries of the gas volume (dielectric surface) for electrons and ions [10]:

$$\Gamma_e = K_{sads} n_e - K_{sdes} n_{se} + K_{srec} n_e n_{si} \quad (5)$$

$$\Gamma_i = K_{sads} n_i + K_{srec} n_i n_{se} \quad (6)$$

$$\Gamma_{i2} = K_{sads} n_{i2} + K_{srec} n_{i2} n_{se} \quad (7)$$

n_{se} and n_{si} are the accumulated surface electron and ion density respectively at the dielectric surfaces. These surface densities are governed by the following ODEs:

$$\frac{dn_{se}}{dt} = K_{sads} n_e - K_{sdes} n_{se} - K_{srec} n_{se} n_i \quad (8)$$

$$\frac{dn_{si}}{dt} = K_{sads}\, n_i - K_{srec}\, n_{si}\, n_e \qquad (9)$$

The K coefficients describe the rate of the different physical processes occurring due to the interaction of the electrons and ions with the dielectric barrier material. The values used are given in the Appendix.

The boundary condition for the rest of the particles is zero density at the dielectric surfaces.

b) Boundary Conditions on Poisson's equation:

A flux discontinuity occurs at both dielectric surfaces because of the net accumulated surface charges ρ_s :

$$\varepsilon_1 E_1 - \varepsilon_2 E_2 = \rho_s \qquad (10)$$

One of the outer electrodes has a zero potential. Electric field is specified at the other outer electrode to perform an injected current condition: $E_s = \frac{1}{A\varepsilon_d}\int i_{DBD}\, dt$ (11)

$\varepsilon_d = \varepsilon_o \varepsilon_r$, ε_r is the relative permittivity of the dielectric material used. A is the cross section area

4.2 Initial Conditions

The initial condition for the ion n_i and electron n_e densities is an equal and uniform density across the gap length. Both densities have to be the same to preserve the electro-neutrality of the gas. For the rest of the variables, the initial condition is zero.

4.3 Energy Calculations

The input energy in one cycle of length T is calculated as

$$E_{in} = \int_{t_0}^{t_0+T} v_{DBD}\; i_{DBD}\; dt \qquad (12)$$

The output optical energy at the wavelength λ in one cycle is calculated as

$$E_{out} = A\frac{hc}{\lambda}\int_{t_0}^{t_0+T}\int_{0}^{L}\frac{n_\lambda}{\tau_\lambda}\, dx\, dt \qquad (13)$$

h is Planck's constant, c is the speed of light, τ_λ is the life time of the excimer producing the radiation of wavelength λ, n_λ is the density of the excimer and L is the gas gap.

Based on the above mentioned equations the following modules from COMSOL are used to solve the system of equations in 1-D Cartesian space:

I. Transient Diffusion Module
II. Transient Convection Diffusion Module
III. Weak Form Boundary Module

The ODE settings option is used to model the external circuit and to solve for the input and output energies.

5. Results

The DBD lamp used in this model has the following properties:

Gas	Xenon
Gas Pressure	400 Torr
Gap length	4 mm
Barrier ε_r	4
Barrier thickness	2 mm
R_s	1 Ω

The voltage waveform of the supply V_s is a unipolar square pulse. Its frequency is 50 kHz and a peak value of 8kV as shown in figure 3.

The first simulation is done with no external parasitics such that V_{DBD}=V_s. Then, a number of simulations is performed with different values for the external circuit parasitic inductance L_s.

Figure 3 also shows the voltage applied to the DBD V_{DBD} for different values of the external circuit parasitic inductance. Higher parasitic inductance results in decreased rate of rise of the applied voltage to the DBD and a higher peak voltage.

The efficiency of the DBD lamp is given as a function of the parasitic inductance in figure 4. Clearly, as the parasitic inductance increases, the efficiency of the lamp decreases.

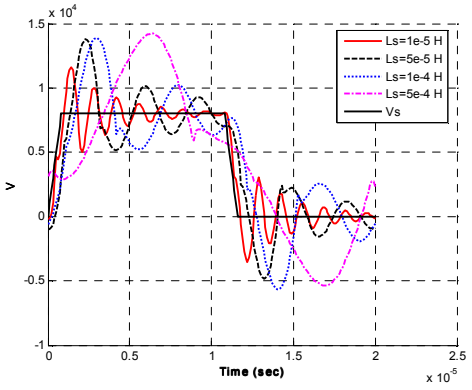

Figure 3. DBD Voltage under different parasitic inductances

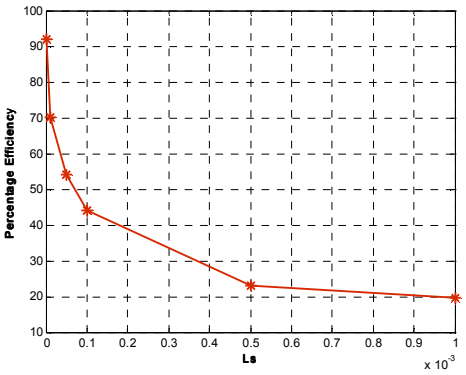

Figure 4. Effect of L_s on DBD Efficiency

6. Discussion

As shown in figure 4, the efficiency of the DBD drops from 92% to about 20% if the external circuit inductance is increased from zero to 1mH. Usually the DBD power supply circuit includes a step up transformer. Since the transformer leakage inductance that appears on the lamp side is proportional to the turns ratio squared, the inductance cannot be neglected in simulating the DBD lamp performance.

The rate of rise of V_{DBD} as shown in figure 3 decreases as the inductance value is increased. It is mentioned in [4, 5] that the voltage rate of rise is one of the main factors affecting the optical efficiency of the DBD lamp. The fast rise-time of the leading edge of the applied voltage heats electrons simultaneously throughout the entire active volume, allowing the breakdown to occur in a diffuse form which is favorable condition for UV production [11].

Another effect of the inductance is the ringing that takes place after the discharge. This ringing results only in power deposition in the plasma without producing UV radiation; therefore the efficiency is also reduced. This has been also experimentally verified in [1-3].

7. Conclusions

A PDE system describing the DBD lamp coupled to an external electric circuit has been solved using COMSOL. Modeling the coupled system shows the effect of the parasitic inductance on the DBD performance.

Modeling the coupled system is also beneficial to the power supply designer as this provides better insight for determining the required ratings for the devices that are used in the power supply.

8. References

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10. Appendix A

A simplified model of the Xenon atom, with only three excited states is considered in this work. The metastable state $^3P_2$ of Xenon is named Xe^*_{met}, the resonant state $^3P_1$ is Xe^*_{res} and all the other excited states are gathered and designated by Xe^*_{exc}. Figure A.1 presents the chemical model adopted in the simulations.

All the reaction rates come from [12]. Collision frequencies and direct ionization coefficient α_{idir} have been calculated using the software package Bolsig [13]. The step ionization coefficient K_{ipal} is taken from [10]. The direct and step ionization coefficients are shown in figures A.2 and A.3 respectively as functions of E/P where E is the electric field and P is the pressure of the Xenon gas.

The source term S_j in the continuity equation is formulated from the chemical reactions as the product of the different species densities involved in the reaction multiplied by the rate coefficient which represents the probability or the rate of this reaction.

The electron mobility and diffusion coefficient are obtained from the software program Bolsig [13], whereas the ion diffusion coefficients and drift velocities are taken from [12] using a linear interpolation.

Figure A.4 shows the electron mobility and diffusion coefficient as a function of the local electric field. The diffusion coefficient and the drift velocity of the ions are plotted in figure A.5 as functions of the reduced electric field E/N. N is the density of the neutral Xenon atom.

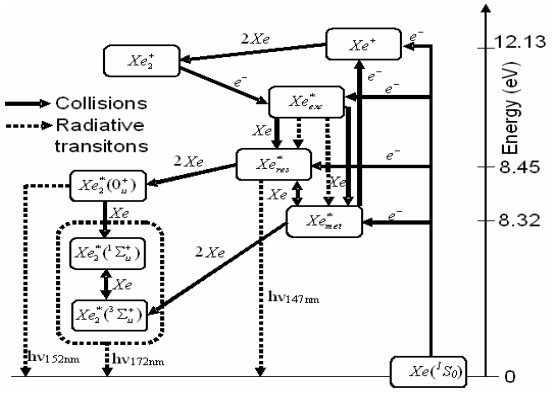

Figure A.1. Chemical model adopted for the modeling

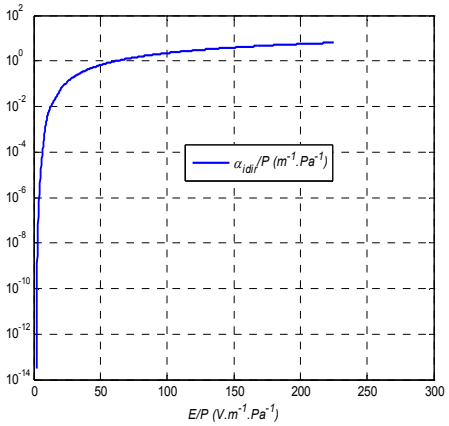

Figure A.2. Direct Ionization Coefficient

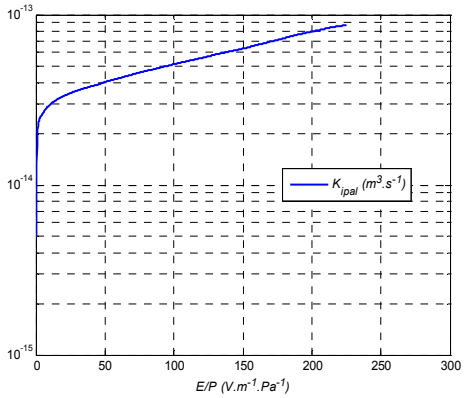

Figure A.3. Step Ionization Coefficient

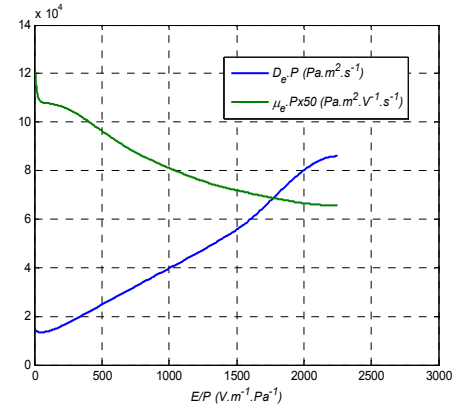

Figure A.4. Electron Transport Coefficients

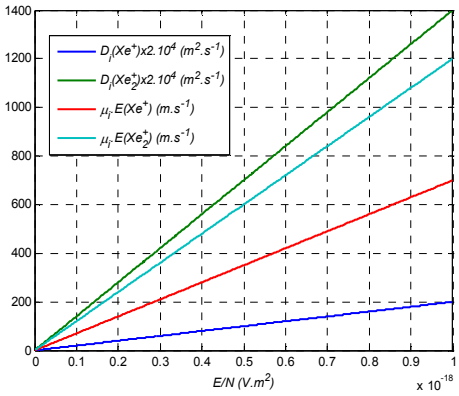

Figure A.5. Ion Transport Coefficients

The K coefficients used in the flux boundary conditions for the electrons and ions have the following the values:

$$K_{sads} \quad 10^{20}$$
$$K_{sdes} \quad 10^{10}$$
$$K_{srec} \quad 100$$

A list of the variables included in this work with the symbol used in the Comsol model is given in table 1.

Table 1: List of Variables

Variable Name	**Symbol**
Voltage	PotentielM10
Electron Density	ElectronM10
Ion Density	IonXeM10
Molecular Ion Density	IonXe2M10
Xe^*_{met}	XeMetM10
Xe^*_{res}	XeResM10
Xe^*_{exc}	XeExcM10
Excimer (1Σ+u)	Exci1SM10
Excimer (3Σ+u)	Exci3SM10
Excimer (O+u)	ExciOuM10
Electron Surface Density	ElectronSurfM10
Ion Surface Density	ChargePosSurfM10
i_DBD	DBD input current
V_DBD	DBD voltage