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ELECTRIC FIELD CONTOURS IN NON-UNIFORM ELECTRODE SHAPE

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ABSTRACT

Silent discharge is well known method to initiate plasma reaction because initial discharge is easily triggered by implementing high voltage to the pair of coupled electrodes with a distance. However, it is very difficult to determine the exact amount of the voltage that initiates the discharge. There are many factors influence the condition of initial discharge such as dimensions, type and geometrical shapes of electrode, thickness of insulation, and type of electric field inside the gap between the electrodes. To obtain lower initial discharge voltage, it is urgent to find the best electrode shape producing electric field contours in line with electron emission triggering. This work examines the behavior of electric field and the applied voltage surrounding electrodes by investigating the mathematical expression for given voltage and generated electric field. The mathematical relationship then gives a basis of theoretical background for electric field contours of two shape electrodes. It is also well known that among many electrodes, the non-uniform geometrical shape is preferred to initiate electric field easily. In this study, a hole shape and a bulge type electrode are investigated.

Keywords: *silent discharge, electric field, differential equation, electrode shape*

ABSTRAK

Peluahan elektron secara senyap adalah metode yang terkenal untuk memulai reaksi plasma karena peluahan awal dalam metode ini mudah dipicu dengan menerapkan tegangan tinggi ke suatu pasangan elektroda yang berpasangan dengan jarak tertentu. Namun, dalam metode ini sangat sulit untuk menentukan jumlah pasti nilai tegangan yang diperlukan untuk memulai peluahan. Banyak faktor yang mempengaruhi kondisi peluahan awal seperti dimensi, jenis dan bentuk geometri elektroda, ketebalan isolasi, dan jenis medan listrik di dalam celah antar elektroda. Untuk mendapatkan tegangan peluahan awal yang lebih rendah, perlu dicari bentuk elektroda terbaik yang menghasilkan kontur medan listrik sesuai dengan pemicu emisi elektron. Dalam tulisan ini terdapat kerja penelitian tentang perilaku medan listrik dan tegangan yang diterapkan di sekitar elektroda dengan menyelidiki ekspresi matematika untuk tegangan yang diberikan dan medan listrik yang dibangkitkan. Hubungan matematis tersebut kemudian memberikan dasar teori latar belakang kontur medan listrik dari dua bentuk elektroda. Berdasarkan hasil yang diperoleh ternayta di antara banyak elektroda, bentuk geometris yang tidak seragam lebih disukai untuk memulai peluahan medan listrik dengan lebih mudah. Dalam tulisan ini, disajikan hasil penyelidikan tentang bentuk lubang dan elektroda tipe tonjolan.

Kata kunci: *peluahan electron senyap, medan listrik, persamaan diferensial, bentuk elektroda*

INTRODUCTION

Silent discharge method is widely used in area of excitation when it is compared to corona and pulse discharge method, consequently silent discharge is able to generate more gas discharges in micro discharge than others [1,2]. Principally the silent discharge is made by a construction of two pair of electrodes, air gap and a dielectric layer covering one or both electrode [2,3]. This paper presents an investigation the behavior of electric field and the applied voltage surrounding electrodes which requires lower initial discharge voltage to support the micro discharge. The work begins with mathematical investigation to know the expression of given voltage and generated electric field. The mathematical relationship then gives a basis theoretical background for electric field contours of two shape of electrode. Several previous works suggested that non-uniform geometrical shape is preferred to initiate electric field easily [3,4]. Therefore, a hole shape and a bulge type electrode are applied as examples of non-uniform electrode in this study. A computer simulation based on mathematical relationship of a given voltage and a generated electric field is carried out to obtain electric field contours which support electron emission.

THEORETICAL BACKGROUND

When the electrode material is injected by external voltage source, the relation among the electric field (**E**) in the conductive material, current density (**J**), conductivity (σ) and electrical field (**E**) can be written as [5,6]:

$$\mathbf{J} = \sigma \mathbf{E} \tag{1}$$

Meanwhile the total current (I) flows through the electrode is formulated by

$$I = \left[\ \mathbf{J} \bullet \hat{x} \right] \Delta s \tag{2}$$

where $\hat{x}$ is unity vector along x-axis and Δs is area surface in where the current flow.

A change of magnetic density in a loop area per unit time will generate electrical field, i.e. by virtue of Faraday's law.

$$\oint \mathbf{E} \bullet d\mathbf{l} = \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{dt} \tag{3}$$

The notation **B** is known the induced magnetic field. The Equation (3) can be expressed also as

$$\nabla^2 \mathbf{E} = -\nabla \frac{\partial \mathbf{B}}{dt} \tag{4}$$

By considering magnetic permeability (μ) in relation between induced magnetic flied (**B**) and magnetic field (**H**) in equation (5)

$$\mathbf{B} = \mu \mathbf{H} \tag{5}$$

It is important to replace **E** and **B** in equation (4) with equation (1) and (5) to get new an equation in Equation (6).

$$\frac{1}{\sigma} \nabla^2 \mathbf{J} = -\mu \nabla \frac{\partial \mathbf{H}}{dt} \tag{6}$$

By using identity vector rule, $\nabla \times (\nabla \times \mathbf{J}) = \nabla(\nabla \bullet \mathbf{J}) - \nabla^2 \mathbf{J}$, equation (6) becomes

$$\nabla(\nabla \bullet \mathbf{J}) - \nabla^2 \mathbf{J} = -\sigma\mu \frac{\partial}{dt}(\nabla \times \mathbf{H}) \tag{7}$$

The current entering a volume is the same as a current leaving the volume, thus overall sum of all current vector in the volume is zero. This phenomenon is represented by $\nabla \bullet \mathbf{J} = 0$ is also known as an electric continuity. Furthermore Equation (7) can be re-written as:

$$-\nabla^2 \mathbf{J} = -\sigma\mu \frac{\partial}{dt}(\nabla \times \mathbf{H}) \tag{8}$$

According to Maxwell's equation [6, 9], magnetic field intensity (**H**) in the loop of area is equal to current density (**J**) and the change of electric flux density (**D**) per time, i.e.

$$\oint \mathbf{H} \bullet d\mathbf{l} = \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{dt} \tag{9}$$

Equation (9) can be modified by replacing $\nabla\times\mathbf{H}$ to be Equation (10)

$$-\nabla^2\mathbf{J} = -\sigma\mu\frac{\partial}{dt}\left\{\mathbf{J}+\frac{\partial\mathbf{D}}{dt}\right\} \quad (10)$$

The relation between electric flux density (**D**) and electric field (**E**) is composed by the use of permittivity of material (ε) and it written as:

$$\mathbf{D} = \varepsilon\mathbf{E} \quad (11)$$

Current density (**J**) is also known as expression of $J = J_0 e^{j\omega t}$ when current density is in sinusoidal waveform [7]. The first derivative of *J* is written as:

$$\frac{\partial J}{dt} = j\omega J_0 e^{j\omega t} = j\omega J \quad (12)$$

By considering Equation (12) into Equation (10), then it is important to rewrite:

$$-\nabla^2 J + j\sigma\mu\omega J + \sigma\mu\frac{\partial^2 D}{dt^2} = 0 \quad (13)$$

Meanwhile, the electric field (**E**) is also defined as $E = E_0 e^{j\omega t}$ when electric field is in sinusoidal waveform. The first derivative of *E* is written as:

$$\frac{\partial E}{dt} = j\omega E_0 e^{j\omega t} = j\omega E \quad (13)$$

and the second derivative of *E* is written as:

$$\frac{\partial^2 E}{dt^2} = -\omega^2 E_0 e^{j\omega t} = -\omega^2 E \quad (14)$$

Taking Equation (1), (13) and (14), then the equation for electric field (*E*) can be expressed as:

$$-\sigma\nabla^2 E + j\sigma^2\mu\omega E + \sigma\mu\varepsilon\omega^2 E = 0 \quad (15)$$

If the Equation (15) is divided by σμ, then differential equation of electric field can be expressed in Equation (16) to ease the solution using numerical method

$$\frac{\partial^2 E}{dt^2} = \mu\left(j\sigma\omega + \varepsilon\omega^2\right)E \quad (16)$$

COMPUTATIONAL RESULT

To have an illustration about the contours of electric field in the given electrode shape, it is useful to investigate the behavior of given voltage and the electric field expression in Equation (16). Partial Differential Equation (PDE) toolbox provided in Matlab gives the execution of the electric field on electrodes [8]. Based on previous work, among many of electrodes, the non-uniform geometrical shape is most preference to initiate electric field [4]. In this study, two geometrical shape of copper electrodes are (1) a hole shape and (2) a bulge type electrode. These electrodes are placed in a pair with air space. The conductivity of copper is 5.8×10^7 S/m, and relative dielectric permittivity of air is close to 8.8×10^{-12} F/m [9].

Figure 1 shows the distribution of Electric field *J* for a hole shape copper electrode. Voltage source magnitude is 10kV at frequency of 30 kHz. The width in vertical axis indicates the thickness for electrodes and air gap. The length specifies the span of electrodes and air gap. All dimensions are in centimeter (cm). The air space gap is 0.5 cm. The field spreads along the electrode surface, however at the hole surface, the contours of electric field are sagging. The convexity of electric field causes weak barrier field reaching the opposite electrode. Higher voltage is required to be injected to the electrode to make a perfect the electric barrier. It is recorded in previous records that a weak barrier in electric field gives a less impact to break the molecules gas to form plasma.

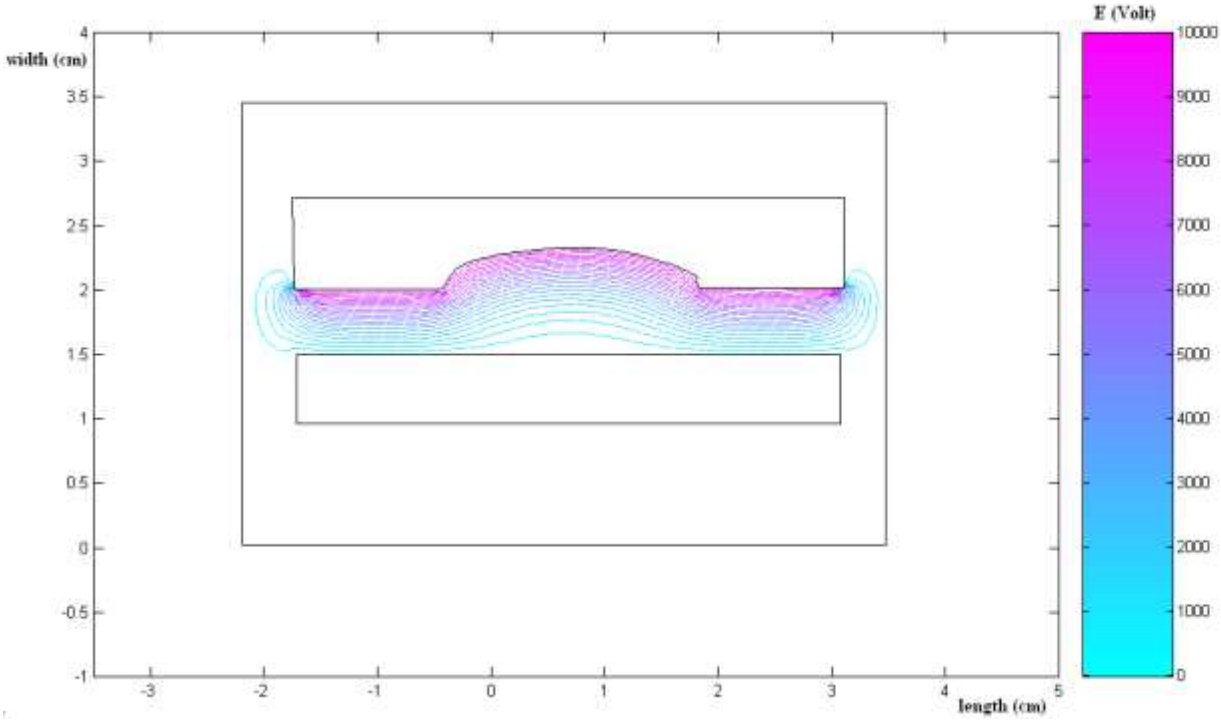

Figure 1. Electric field at a hole type copper electrode.

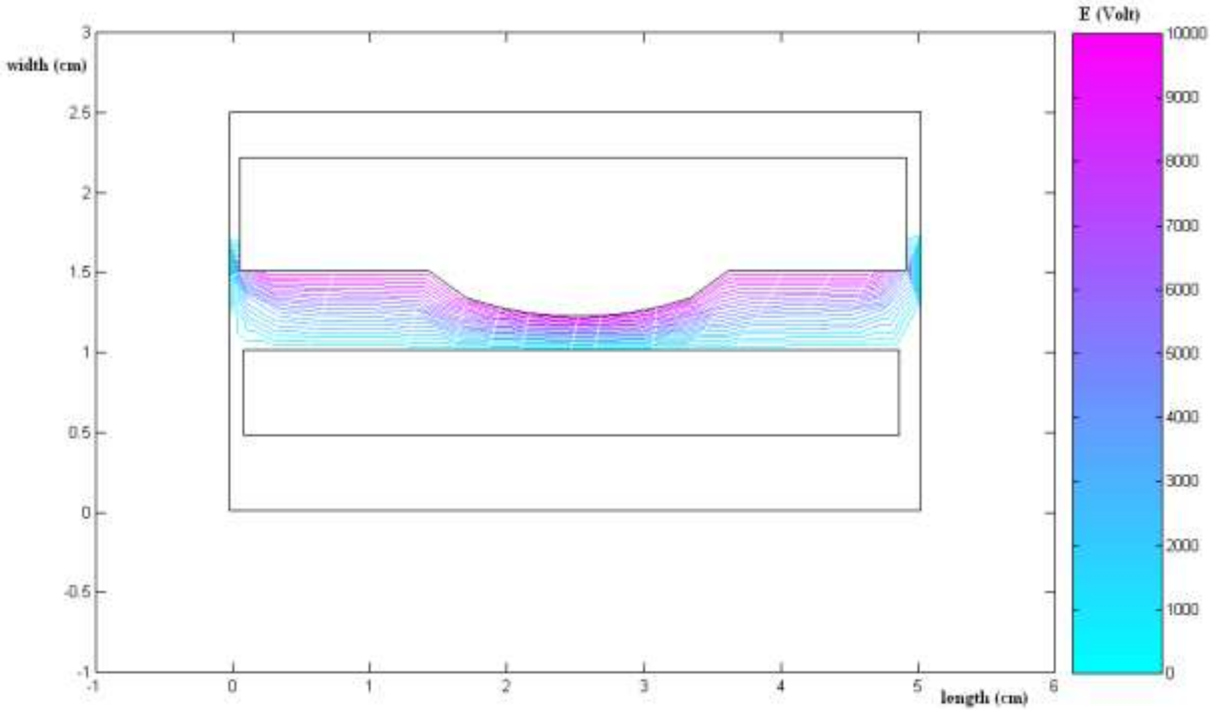

Figure 2. Electric field at a bulge type copper electrode.

Figure 2 shows the stronger distribution of electric field a bulge type copper electrode at the same voltage magnitude surface 10kV with frequency 30 kHz. The air space gap remains at

0.5 cm. The field spreads strongly along the electrode surface. The strongest field occurs at the tip of bulge electrode. The field jots out reaching the opposite electrode. The contours of electric field follow the concavity of electrode surface, forms almost perfect barrier and finally it will contribute to more effective effort in breaking molecules gas to form plasma.

From Figures 1 and 2, it is clear that the bulge type copper electrode initiates electric field easily than the hole type electrode. A thorough electrical field barrier has been formed more intensively by using a bulge type electrode and the field reach the opposite electrode with higher amount than the hole type electrode. It is expected that intensive contours of electric field will ease the silent discharge process to break the incoming molecules of gas.

CONCLUSION

The mathematical relationship as a basis of theoretical analysis for generated electric field contours of electrodes has been exposed for the given voltage. The computational results are able to express the contours of electric field for the adjacent electrode at high voltage and high frequency. A simulation carried out based on mathematical expression has shown that a bulge type copper electrode has successfully initiate electric field easily than the hole type electrode and formed an electric field barrier along the electrode reaching the opposite electrode with stronger amount of field. A thorough and strong electric field barrier generated by bulge electrode will ease the silent discharge mechanism to break the injected molecules of gas and transform the gas into plasma.

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