

Dissertation

STUDY OF ELECTRICAL AND DIELECTRIC PROPERTIES OF DIELECTRIC BARRIER DISCHARGES (DBD) GENERATED BY SILICON DIODE FOR ALTERNATING CURRENT (SIDAC) IN WATER



Kanazawa University

Graduate school of Natural Science and Technology
Electrical Engineering and Computer Science

| | |
|--------------------|------------------------|
| Student ID No. | 1524042010 |
| Name | TRUONG THI HOA |
| Chief advisor | Prof. Yoshihiko Uesugi |
| Date of submission | Sep, 2018 |

Abstract

This work deals with dielectric barrier discharge (DBD) generated in bubbles in water using Silicon Diode for Alternating Current (SIDAC). Dielectric-barrier discharge (DBD) is a discharge obtained in gas space between two electrodes, in which at least one of the electrodes is covered by a dielectric material. The dielectric layers in the configuration of the DBD reactor make this discharge characterized as a capacitive load, self-terminated discharge, which is generated by a high frequency alternating voltage source or a high frequency repetitive pulse power source. SIDAC or Silicon Diodes for Alternating Current is a bidirectional high voltage switching device designed for direct interface with the power line. It has high break-over voltage and power handling capabilities. The high-speed switching characteristic of SIDAC has been used for generating low-cost high voltage pulses with tens of kV derivation that have been effectively applied to DBD generation.

In this study, DBD plasmas in water were investigated as a sequence of a bubble formation and an electronic process within the bubbles. A cylindrical electrode inside a glass tube with a number of microsize holes and an inexpensive circuit using a number of SIDAC connected to a high voltage transformer at commercial frequency have been used. The gas bubbles are simply produced at initial stage by gas flow through microsize glass holes. When applied voltage meets or exceeds breakover voltage of the series connecting SIDACs, these SIDACs switch from a blocking state to a conducting state. Then, high voltage pulses with tens of kilovolt derivation are generated, as the bubble formed an electrical breakdown instantaneously takes place within the bubble. The generation of such DBD plasma should be analyzed sufficiently when its characteristics are governed by two switches: the SIDAC switching characteristic and the dielectric layers.

Additionally, one of the constraints DBD application to waste water treatment is the requirement of the expensive and complex power source configurations that could make the DBD installation expensive and selective. The prospect of an increase in the market share of the application of DBD generation still faces the challenges oriented with the need of the compact and affordable power supplies. Therefore, this work also focused on design, construction, and optimization of configuration of a novel high

voltage pulse power source for large-scale dielectric barrier discharge (DBD) generation by using a device called Silicon Diodes for Alternating Current (SIDAC) and the self-terminated characteristic of DBD without external controlling. The DC power supply has been designed in a simple modular structure, non-control requirement, the transformer elimination, minimum number of levels in voltage conversion required to achieve the desired operating condition leading to a reduction in size, weight, simple maintenance and high scalability of the DBD generator. Fundamental results and conclusions achieved during this work have been published in scientific journal, presented at conferences and attached in Appendices

Table of Contents

| | |
|--|-----------|
| Abstract..... | i |
| Table of Contents..... | iii |
| List of Figures..... | iv |
| List of Tables..... | vii |
| Acknowledgements..... | viii |
| Chapter 1: Introduction | 1 |
| 1.1 Background OF PLASMA | 2 |
| 1.2 Dielectric Barrier Discharges | 10 |
| 1.3 Silicon Diodes for Alternating Current (SIDAC)..... | 16 |
| Chapter 2: Properties of Dielectric Barrier Discharges (DBD) generation using Silicon Diodes for Alternating Current (SIDAC) in water .Error! Bookmark not defined. | |
| 2.1 DBD generation by using SIDAC in gas phase..... | 20 |
| 2.2 DBD generation by using SIDAC in bubbles in water..... | 23 |
| Chapter 3: Novel design of high voltage pulse source for efficient DBD plasma generation by using SIDAC | 33 |
| 3.1 High voltage pulse generation | 34 |
| 3.2 Testing performance with a load of resistor | 36 |
| 3.3 DBD Generation by designed DC high voltage pulse source in gas phase | 43 |
| 3.4 DBD Generation by designed DC high voltage pulse source in bubbles in water | 49 |
| 3.5 Summary..... | 52 |
| Chapter 4: Conclusions and future work | 54 |
| Chapter 5: Supplements | 56 |
| 5.1 Strong effect of stray capacitance caused by short distance between wire and ground..... | 56 |
| 5.2 Improvement in isolation of circuits from ground..... | 58 |
| 5.3 Discharge lagging behind SIDAC switching time due to low discharge frequency in glass DBD reactor..... | 63 |
| 5.4 Increase discharge frequency in case of using DC power supply by connecting to DBD reactor an additional parallel resistor | 70 |
| 5.5 Replacing the ground electrode of DBD generation in bubbles in water from wire insulated by PTFE to cylindrical type insulated by glass | 73 |
| References | 77 |
| Appendices..... | 81 |

List of Figures

| | |
|--|----|
| Figure 1-1 Four states of matter | 3 |
| Figure 1-2 Plasma in Nature..... | 3 |
| Figure 1-3 Maxwell-Boltzmann distribution of velocities [1] | 5 |
| Figure 1-4 Maxwell-Boltzmann distribution of velocities as progressive temperature [1]..... | 6 |
| Figure 1-5 Classifications of plasma in terms of electron density and temperature [1]..... | 8 |
| Figure 1-6 Typical electrode arrangements of barrier discharges [17] | 11 |
| Figure 1-7 Sketch of a microdischarge and a simple equivalent circuit [4]..... | 12 |
| Figure 1-8 Schematic of applied voltage $v(t)$, gap voltage $v_g(t)$, breakdown voltage (v_b), main current $i(t)$, displacement current $i_{disp}(t)$, and discharge current $i_{dis}(t)$ [20]..... | 15 |
| Figure 1-9 V-I characteristic of SIDAC (K1V38 (W)) | 17 |
| Figure 2-1 DBD generation in gas phase- experimental setup..... | 20 |
| Figure 2-2 DBD generation in gas phase -experimental result, DBD photograph (a) discharge waveform in one cycle of applied voltage (b), and enlargement waveform of one typical discharge (c) | 21 |
| Figure 2-3 DBD generation in bubbles in water- experimental setup..... | 23 |
| Figure 2-4 DBD generation in bubbles in water- experimental result, DBD photograph (a), discharge waveform in one cycle of applied voltage (b), and enlargement waveform of one typical discharge (c) | 25 |
| Figure 2-5 Schematic of discharge progress in bubbles in water, positive discharge (a), and negative discharge (b)..... | 26 |
| Figure 2-6 Equivalent circuit of DBD reactor in gas phase (a), in water (b) | 26 |
| Figure 2-7 Emission spectra of the DBD plasma generated in 0.02 slm O ₂ and 5slm He mixture gas, measurement setup (a), and result (b) | 27 |
| Figure 2-8 Chemical structure of MB, C ₁₆ H ₁₈ N ₃ ClS | 28 |
| Figure 2-9 Absorption spectra of MB solution at different concentration levels..... | 29 |
| Figure 2-10 Calibration curve of average absorbance versus concentration | 29 |
| Figure 2-11 Time evolution of MB concentration treated by DBD plasmas | 30 |
| Figure 2-12 Absorption spectra of MB solution exposed to O ₂ added Ar plasma with the increase of treatment time..... | 30 |
| Figure 2-13 Fading color in MB samples by 5 slm He mixed 0.02 slm O ₂ plasma | 31 |
| Figure 3-1 Modular structure of high voltage pulse source | 34 |

| | |
|--|----|
| Figure 3-2 Setup of experiment with a resistor, diagram of circuit connection (a) and equivalent circuit (b)..... | 37 |
| Figure 3-3 Results of experiment with a resistor, overall waveform in case of positive pulses (a), overall waveform in case of negative pulses (b), enlargement waveforms around conductive state of SIDAC (c), and enlargement waveforms around positive current peaks (d)..... | 38 |
| Figure 3-4 Dependence of leakage current (i_{Leak}) on voltage derivative(dvR/dt), estimated stray capacitance | 40 |
| Figure 3-5 Equivalent circuit with a resistor load used for calculating the efficiency of the whole system | 41 |
| Figure 3-6 Capacitor (1.25 nF) voltage waveform..... | 41 |
| Figure 3-7 . Experimental setup of DBD generation in gas phase using the DC power supply, diagram of circuit connection (a) and equivalent circuit (b)..... | 43 |
| Figure 3-8 Results of experiment with load of DBD in gas phase, overall waveform in case of positive pulses (a), overall waveform in case of negative pulses (b), and enlargement waveforms around negative current peaks (c)..... | 46 |
| Figure 3-9 Equivalent circuit with a gas phase DBD load used for calculating the efficiency of the whole system..... | 48 |
| Figure 3-10 Enlargement waveform of voltage on charge capacitor (1.25 nF) of DBD generation using the DC power supply in bubbles in water | 48 |
| Figure 3-11 Experimental setup of DBD generation in water using the DC power supply | 49 |
| Figure 3-12 Experimental results of DBD generation in water using the DC power supply overall waveform (a) and typical enlargement waveform (b)..... | 50 |
| Figure 3-13 Enlargement waveform of voltage on charge capacitor (1.25 nF) of DBD generation using the DC power supply in bubbles in water | 51 |
| Figure 5-1 Setup of testing experiment on vibration isolation table..... | 57 |
| Figure 5-2 Testing result shows strong effect of stray capacitance | 58 |
| Figure 5-3 Setup of testing experiment on a resin sheet | 59 |
| Figure 5-4 Overall waveform obtained from testing experiment on the resin sheet | 60 |
| Figure 5-5 Enlargement waveforms from negative side of testing experiment on resin sheet..... | 61 |
| Figure 5-6 Enlargement waveforms from positive side of testing experiment on resin sheet..... | 61 |
| Figure 5-7 Spacer used for separating circuit element from ground..... | 62 |
| Figure 5-8 Experimental result of DBD generation in gas phase using the DC power supply in glass reactor..... | 64 |
| Figure 5-9 Setups of experiment with conventional AC power supply | 64 |

| | |
|--|----|
| Figure 5-10 Results of experiment with AC power supply at low frequency in glass reactor..... | 66 |
| Figure 5-11 Results of experiment with reactor made from Ceramic plates and Primary voltage of 50V, 60 Hz..... | 67 |
| Figure 5-12 DBD reactor configuration..... | 68 |
| Figure 5-13 Experimental results obtained by using reactor of ceramic plates..... | 69 |
| Figure 5-14 Experiment setup with load of DBD reactor..... | 71 |
| Figure 5-15 Results of experiment with load of DBD reactor paralleled to additional resistor..... | 72 |
| Figure 5-16 Electrode configuration..... | 74 |
| Figure 5-17 Experimental setup of DBD generation in water..... | 75 |
| Figure 5-18 Experimental results with the new ground electrode, 500 sccm He gas flow..... | 76 |

List of Tables

| | |
|--|----|
| Table 1-1 Typical operation conditions of barrier discharges in air [18] | 11 |
| Table 1-2 Characteristic of a microdischarge channel in air at atmospheric pressure [18]..... | 13 |
| Table 1-3 Electrical Characteristic of SIDAC (K1V38 (W) Shindengen Electric Mfg.Co.Ltd) | 17 |
| Table 2-1 Experimental condition..... | 20 |
| Table 3-1 Specification of designed pulse source..... | 36 |
| Table 3-2 Experimental condition for DBD generation using the DC power supply | 44 |
| Table 5-1 Experimental condition (testing experiment) | 59 |
| Table 5-2 Condition of experiment with 60 Hz AC power supply | 64 |
| Table 5-3 Properties of Pyrex glass plate and Ceramic plate..... | 68 |
| Table 5-4 Condition of experiment of DBD generation using DC power supply and glass reactor connected parallel to an additional resistor | 71 |
| Table 5-5 Condition of experiment of DBD generation in bubbles in water using the DC power supply and cylindrical glass electrode | 74 |

Acknowledgements

I am grateful to Vietnamese government (project 911) for the financial support.

I would like to express my special appreciation and thanks to my supervisors Prof. Yoshihiko Uesugi , Prof. Yasunori Tanaka , Prof. Tatsuo Ishijima., for the continuous support of my Ph.D study and related research, for your patience, motivation, and immense knowledge. Your guidance helped me all the time of doing research.

Besides my supervisors, I would like to thank my groupmates Yusuke Heira, Misaki Hayashi for instructions, discussions from my first day I arrived Japan and for all days working together. And I thank my labmates for technical support and for all the fun we have had.

A special thanks to my family. Your love encourage me every day and provide me endless inspiration. And a special thanks to teachers of Asahimachi nursery school who help me taking care of my two kids so I can focus on my research.