Discharge Characteristics of Dielectric Barrier Discharge (DBD) based VUV/UV Sources

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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 coaxial and planar geometry of DBD (gas gap: 1-3 mm) made of quartz with N₂/Ar/Xe gas at different pressures. A proper ultra high vacuum system and gas filling system has been made for the processing & characterization of DBD tubes. A RF generator (20-100 kHz, 0-2.4 kV peak) is used for discharges in DBD tube. A stable and uniform discharge is produced in the gas gap between the dielectric barrier electrodes. The discharge characteristics have been analyzed by V-I characteristics & Lissajous figure and found that the spatial discharge processes varies strongly according to the applied voltage waveform, pressure of filled gas and geometry of tube.

1. Introduction
A dielectric barrier discharge (DBD), sometimes referred to as a barrier discharge or a silent discharge, is a type of discharge in which at least one of the electrodes is covered with a dielectric material. This dielectric layer acts as a current limiter and prevents the formation of a spark or an arc discharge. The electrical energy coupled into a DBD-plasma is mainly transferred to energetic electrons, while the neutral gas remains close to ambient temperatures. The non-equilibrium plasma that is produced can be operated at elevated pressures. This combination of plasma properties makes it a unique device with many industrial applications. DBDs have been extensively studied for over a century. Their principles have been thoroughly investigated and are described in numerous papers, for example1-4. Traditional industrial applications range from ozone synthesis in oxygen, surface modification of the polymers, PCVD, pollution control, air to cleaning of flue gases. Nowadays, DBDs are also used in plasma display panels, high-power CO2 lasers and excimer UV/VUV lamps3. 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. For most operating conditions, a DBD consists of a (large) number of discharge filaments, which have a nanosecond duration and are randomly distributed over the
dielectric surface. These filaments, also known as microdischarges, are the active regions of a DBD in which active chemical species and UV/VUV radiation can be produced. These microdischarges act as individual discharges which work independently of one another. The discharge dynamics and chemistry of individual microdischarges have been studied in detail, both through modeling and experimental investigations.

In the 1980s, a different type of discharge mode in DBDs was observed. Under certain operating conditions, the discharge appears as a diffuse glow, covering the entire electrode surface uniformly. Since then numerous investigations have been performed to understand and explain the physical basis of this discharge mode. Several mechanisms have been discussed to explain the generation of diffuse DBDs. These include gas pre-ionization by electrons or metastable from previous discharges and interaction between the plasma and the dielectric surfaces. Since atmospheric pressure conditions are most suitable for many DBD applications, the research on the properties of the different discharge modes has focused mainly on atmospheric pressure conditions rather than on the low pressure regime. However, a detailed description of the behaviour of DBDs at low pressure may contribute to a better understanding of the fundamental processes involved in DBDs.

The aim of the research described in this paper is to investigate the behaviour of DBDs in the pressure range from 50 to 1000 mbar for gases like nitrogen and argon. The experiments have been performed using coaxial DBD tube. We characterized the discharge properties by recording voltage and current waveforms. Dependence of breakdown voltage of DBDs on pressure and applied voltage waveform has been analyzed. We also analyzed the appearance of filaments and their diffusion through out the BDB surface as a function of applied voltage waveform.

2. Experimental arrangement

2.1 Vacuum processing system

In principal, a DBD source is being operated on large range of parameters (thickness of dielectric layer, gas gap, gas pressure etc) having interdependence relation between all the parameters. To achieve desired radiation (172 nm peak for Xe) for long operation lifetime and to improve efficiency of compact sealed-off excimer source requires a demountable DBD characterization setup of DBD source with optimization of geometrical and electrical parameters. Based on optimization parameters, sealed off DBD tubes have been fabricated. Figure 1 represents the schematic of the vacuum system, used for the processing and characterization of different discharges occurring on dielectric barrier discharge tubes. The vacuum system mainly consists of experimental chamber with VUV/UV characterization apparatus, processing system and gas filling system.

The processing system consists of a 220 l/s triode sputter ion pump (SIP). This pump has an ultimate vacuum capability of 10^-9 torr. This pump starts working at 10^-3 torr, hence it requires a TMP backing pump. The TMP is used for pumping out different gases from the tubes, backing pump for SIP so on. There is gas filling system consists of N2/Ar/Xe or any other gas cylinder supported by gas plumbing lime, valves and necessary accessories. The gas filling system facilitates entry of 99.99% pure gas from high pressure cylinder to the tube through the gas inlet section of UHV processing system. An automatic pressure controller through a servo controlled leak valve normally controls the gas pressure inside the UHV system. The check valve maintains unidirectional flow of gas. The compact dual full range gauges (Pfeiffer make) are used for the measurement of pressure between 10^-9 mbar to 1 bar.

Two different quartz DBD tubes have been designed for the experiments. The one port of the fabricated DBD tubes have been connected to the pumping system and the other port have been sealed off by glass blowing technique. The DBD tube should be kept horizontally on the insulating bed of the processing system. The baking oven has been used to bake the tube up to 450 °C. For more than six hours operation of the baking system at 450 °C, a good UHV has been achieved inside the tube through the SIP pumping system. After achieving a UHV inside the DBD tube, the pure gas from the
respective cylinders are allowed to fill inside the DBD tube. Opening and closing the UHV valve connected between DBD tube and TPM control the gas pressure inside the tube. Two different coaxial quartz DBD tubes have been fabricated for the experiment. Figure 2 represents the photo and schematic of the quartz DBD tube with dimensions used for our experiment.

Figure 1. Schematic view of vacuum system for DBD experiment (a) Experimental chamber, (b) vacuum processing system and (c) gas filling system

Figure 2. Quartz DBD tube (a) Picture and (b) schematic view

Length = 300 mm
Outer diameter = 40.0 mm
Inner diameter = 30 mm
Width of outer barrier = 1.5 mm
Gas gap thickness = 2.0 mm
Width of inner barrier = 2.0 mm
2.2 Electrical diagnostic system

The experimental setup is shown in figure 3. Two quartz tubes of variable length (300 and 200 mm) have been used for experiment. A sinusoidal voltage supply (Huttinger HF Generator TIG 10/100 PSC) up to 4.8 kV peak to peak with frequencies from 20 to 100 kHz has been applied to the discharge electrodes for the generation of microdischarges. The variable oscillator circuit capacitance of the generator (parallel connection of individual capacitors within a block) makes it possible to change the operating frequency and matching to the output load. The outer part of the tube is covered by copper wire mess electrode and the inner part of the tube is covered by metal foil. The outer wire mess electrode acts as cathode and the inner foil electrode as anode. The wire mess electrode helps the radiation to come out of the tube for spectroscopy analysis. The high voltage probe (Tektronix P6015A) measures the voltage across the DBD tube and current transformer (PEARSON current monitor, Model 110) measures current through the DBD tube. The discharge current and applied voltage waveforms are recorded with a digital four-channel oscilloscope TDS 3034B (300 MHz, 2.5 GS s⁻¹) from Tektronics. The oscilloscope is interfaced to the personal computer for real time analysis and recording the voltage and current waveform from the oscilloscope.

![Figure 3. Schematic diagram of the experimental set-up](image)

3. Results and discussions

3.1 Discharge mode

In our experiment the voltage applied to the metal foil electrode and mesh electrode was manually increased very slowly. The pressure of argon gas inside the DBD tube was varied from 60 mbar to 1000 mbar. When the applied voltage rose to certain value $V_{br}$ (Breakdown voltage), discharge began with some filaments distributed on the dielectric wall, but the intensity of the light emitted from the discharge gap was so weak that it could be observed by naked eyes only in a dark room. If the applied voltage is increased further the filaments get diffused. Figure (4a) is the image of discharge taken with digital camera (SONY make). It can be seen from the image that the discharge is radially homogeneous and covers the entire surface of the electrode. Figure 4 (b) and (c) are the current trace together with applied voltage and Lissajous figure, respectively. As the applied voltage increase further little bit, some discharge noise generated on the system and the discharge light a little bit more intensive. At some high voltages many current pulses are superimposed on the discharge current showing that more filaments are generated as shown in figure 5.

As it is known, DBD is often composed of many discharge filaments whose development occurs in some tens of nanoseconds, the best way to be sure that they do not develop is to take a picture with 10 ns exposure time. This analysis we will do in future using spectroscopy and ICCD camera. There is another method of distinguishing between filamentary discharge and homogeneous discharge, by using two figures: the Lissajous figure of voltage-charges and the current pulse shape. A filamentary discharge is composed of a number of current pulses per half voltage cycle and its Lissajous figure is drawn as a parallelogram, while a single current pulse per half voltage cycle characterizes a...
homogeneous discharge and its Lissajous figure appears as only two voltage lines, the top and the bottom lines of parallelogram, because the traces of the two vertical charges lines jump back and forth within so sort a time of only one current pulse that they can hardly be observed. Although the discharge shown in figure 4 (a) looks homogeneous, it is a filamentary discharge rather than a real homogeneous discharge according to the Lissajous figure shown in figure 4(c) and the current pulse shapes shown in figure 4(b).

![Image](a)

![Image](b)

Figure 4. DBD tube in argon atmosphere at 60 mbar (a) The homogenous looking discharge, (b) the applied voltage and discharge current and (c) the Lissajous figure of the discharge.

![Image](a)

![Image](b)

Figure 5. DBD in argon atmosphere when applied voltage is increased little bit (a) The filamentary discharges (b) applied voltage and discharge current.

3.2 Breakdown voltage of the gas gap
In the case of a DBD, the discharge is in repetitive mode, and the residually charged particles and metastable atoms or molecules from the previous discharge will influence the next breakdown. An ac voltage with a frequency of 20 to 100 kHz and amplitude up to 4.8 kV peak to peak is applied to ignite
and sustain the DBD discharge. When the voltage polarity is reversed, the applied voltage is added to memory due to the polarization of the dielectric surface. Therefore, the sustaining voltage for the DBD is obviously lower than the ignition voltage required for the first time. Some experimental values of breakdown voltage were deduced at different operating frequencies. By taking into account the values obtained in these experiments, the following semi-empirical equation for the breakdown voltage as a function of the operating frequency was proposed:

\[
V_{bd} = \frac{K(C_d / C_g)^2}{\ln(f)}
\]

The values of \(C_d\) and \(C_g\) are calculated by using the coaxial model. The calculated capacitances are 80.38 pF and 59.205 pF for dielectric barrier and gas gap respectively. The total capacitance measured by LCR meter is 34.05 pF and the calculated capacitance is 34.09 pF. By operating at high frequencies, the DBD discharge presents the advantage of higher memory voltage formation by charge accumulation on the dielectric layer. This memory voltage decreases the breakdown voltage \(V_{bd}\) and increases the gas voltage with frequency. Nevertheless, at much higher frequencies (several megahertz) this effect vanishes and the equation is no longer valid. In the case of nitrogen gas this empirical relation was quiet matching with the experimental results. In the case of argon gas at 1000 mbar, the breakdown voltages are 600 V and 400 V for 34.8 kHz and 45.7 kHz respectively. It is also observed experimentally that the amplitude of current increases and the value of sustaining voltage decrease with frequency. Figure 6 represents the effect of frequency on breakdown voltage and amplitude of current.

The effect of pressure on the breakdown voltage and the amplitude of the discharge current have been analyzed experimentally. The values of the breakdown voltage and discharge current have been increased with increase in the pressure. It is also seen that the number of current filaments are getting more on the discharge current peak with increase in pressure. The discharge patterns are seen more diffuse at lower pressure (less than 100 mbar) than higher pressure.

![Applied voltage and discharge current waveform for breakdown voltage comparison of DBD tube at 1000 mbar argon](image)

Figure 6. Applied voltage and discharge current waveform for breakdown voltage comparison of DBD tube at 1000 mbar argon (a) At 34.8 kHz frequency and (b) at 45.7 kHz frequency

4. Conclusion

Under the project “development of VUV/UV sources based on DBD”, we have fabricated and tested DBD tubes in nitrogen, argon and xenon atmosphere at various pressures. The discharges are confirmed filamentary in nature and diffuse through the electrode surface.
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