Transition from diffuse to self organized filament in a high frequency DBD

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Depending on the operating conditions, different regimes can be obtained in a Dielectric Barrier Discharge (DBD): filamentary, diffuse/homogeneous or self-organized. For a plane-to-plane DBD operated at high frequency (160 kHz) and at atmospheric pressure in helium gas, we show that the addition of a small amount of nitrogen induces a transition from the homogenous regime to a self-organized regime characterized by the appearance of filaments at the exit of the discharge. In this paper, we detail mechanisms that are responsible of the transition from diffuse mode to this self-organized mode.

1 Introduction

Dielectric Barrier Discharge (DBD) is a discharge established in a gas gap between two electrodes whose at least one is covered by a dielectric layer [1]. Dielectric allows to limit the current of the discharge and to obtain cold plasma even at large *pd* product (*p* is the pressure and *d* the gas gap). Therefore DBD has a lot of application (*e.g.* ozone generator, excimer lamp, plasma display panel (PDP), surface treatment, flow control actuator …).

Usually, DBD works in the so-called filamentary mode, but depending on the gas, the electrical parameters, and the electrode configuration, a homogenous discharge can be generated. Homogeneous DBD have been obtained in helium, argon, and nitrogen [2]. In nitrogen an Atmospheric Pressure Townsend Discharge (APTD) can be generated, while in noble gas it is an Atmospheric Pressure Glow Discharge (APGD). In any case, Townsend breakdown generally leads to homogenous discharge [3], while streamer breakdown leads to random filamentary discharge.

Similarly to what is observed in many other nonlinear systems, DBD can exhibit self-organized patterns. This phenomenon may look like as a spatial organization of filaments [4] usually obtains in filamentary mode but other patterns have been observed: strip, inversed hexagonal, concentric ring [5–7]. The appearance and the dimension of these patterns suggest that these self-organized discharges ignited under a Townsend breakdown. Recently, a hexagonal superlattice pattern has been observed, which consists on several hollow rings equally distributed on the dielectric surface [8]. Observed with short exposure time photographs, a hollow ring is the composition of periodic-driven vibrating motion of discharge filament pairs. Therefore self-organized pattern is not necessary obtain within one discharge, but successive discharges could lead to a pattern. This confirms that self-organized denomination describes different kinds of discharge. This is certainly why it is obtained in a wide spectrum of experimental conditions: self-organized discharge pattern can thus be produced in one [9] or two dimensional discharge gap geometry [5], at low or at atmospheric pressure [6] and under a large range of temperature [10]. However, discharges leading to formation of self-organized pattern are most often produced in noble gases. I any case memory effect seems the cause of self-organized pattern: discharge ignites where charges have been previously deposited (the breakdown in this location being lower). Theses charges are deposited on the electrode in the same location (by the current of the discharge) or in the vicinity (by the low current (dark) between two filaments) of the previous discharge [11].

In this paper we focus on the structure of a 2D-DBD in helium and on the role of the adding of nitrogen on the self-organization. In particular, we focus on the conditions (pressure, flow rate) for which theses patterns are obtained.

2 Experimental setup

The DBD is kept in a closed vessel to perform experiments in a very well controlled atmosphere. The plasma reactor is pumped down to 10^{-3} mbar prior to any experiment, and then is filled up to atmospheric pressure using mixtures of helium and nitrogen. Two mass flow meters allow regulating the amount of helium and nitrogen. The discharge is created between two plane electrodes, square with 3 cm size, each of them covered by a dielectric barrier. The high voltage (bottom) electrode is an alumina plate 625µm thick, the grounded electrode (top) is a glass plate 1.1mm thick.

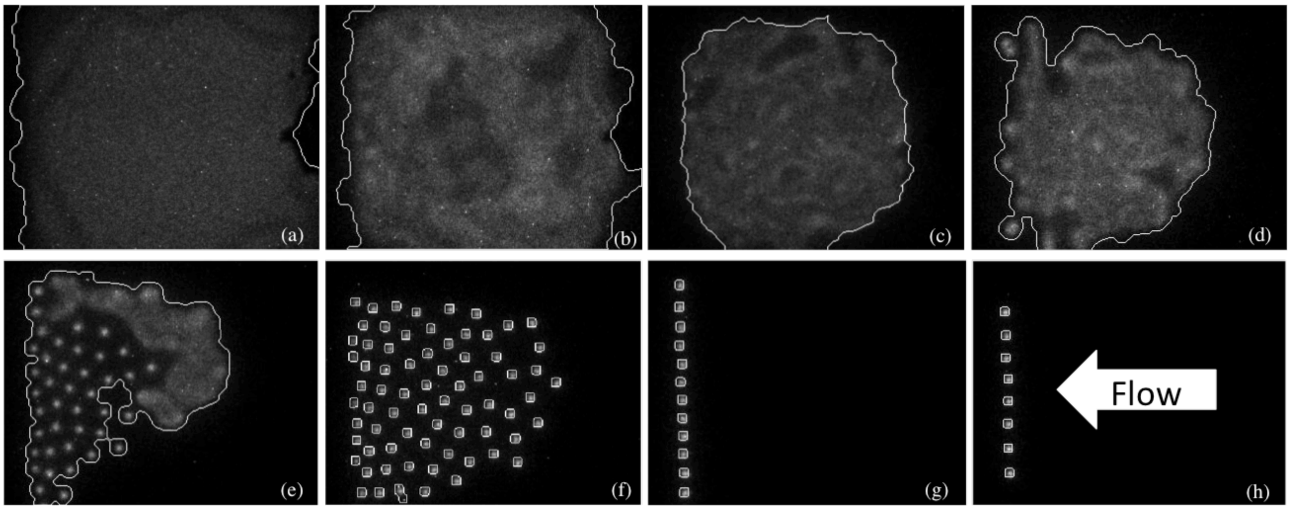

Figure 1: Images of the discharge for increasing concentration of N_2 in He. Exposure time is 6.25 µs (1 period). Whites lines corresponds to the outline of the discharge. (a): 100% H_e. (b): 0,25% N_2. (c): 0,6% N_2. (d): 0,8% N_2. (e): 1,1% N_2. (f): 1,1% N_2. (g): 1,2% N_2. (h): 1,6% N_2.

Both electrodes are separated by a 1mm gas gap. So as to observe the discharge, the top electrode is made of a thin layer of ITO. In order to renew the atmosphere, a gas flow is injected from one side of the discharge (longitudinal gas injection), keeping a constant pressure through a gentle pumping of the vessel.

The DBD is powered by a high frequency (160 kHz) power supply (RFPP-LF 10) associated with a homemade matching network. Voltage is amplified using a transformer (ratio 1:20). The power supply is controlled in power and not in voltage. The electrodes are connected to the secondary of the transformer.

2.1 Discharge area measurement

The discharge is investigated by means of short exposure time pictures, taken with an intensified CCD camera (PI-MAX3, Princeton Instrument) synchronized with the power supply voltage. Images presented in this paper are taken though the top electrode.

The total area of the discharges is deduced from these pictures using an appropriate filter. At first, images are smoothed with an averaging filter in order to reduce the picture noise. Afterwards, an edge filter detects the local maxima of the gradient of the image. As seen in Figure 1 two kinds of discharge are observed: diffuse and filamentary. For diffuse discharge (Figure 1 (a) to (e)), gradients are smaller than for filamentary discharge (Figure 1 (f) to (h)), thus two different edge filters are used: a low detection threshold filter (LF) and a high detection threshold one (HF). The area of the discharge corresponds to the number of pixels inside the white line (see Figure 1).

2.2 Gas voltage calculation

The high voltage applied to the DBD (V) is measured using a 20 MHz high voltage probe, and a current probe measures the AC current (I), with a pass-band limited to 20 MHz. The data are recorded on a 600 MHz oscilloscope LECROY Wavesurfer 64 MXs-A.

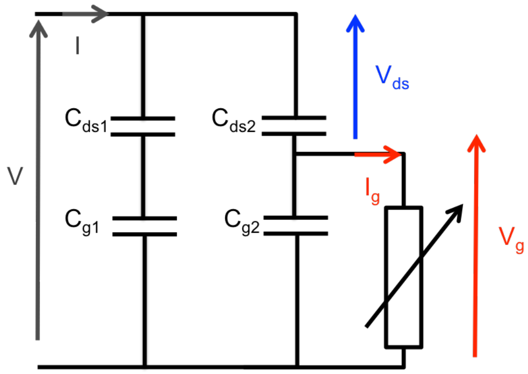

Figure 2: Equivalent circuit of the discharge

Gas current (I_g) and voltage (V_g) are calculated from the equivalent model (Figure 2) as presented in [12]. C_{ds} and C_g are the equivalent dielectric and gas capacity respectively. Theses capacities are split in two circuits C_{ds1}/C_{g1} and C_{ds2} /C_{g2}. Subscript 2 is associated to the discharge zone, and subscript 1 to the rest of the electrode so:

$$C_{gi} = C_g \cdot \frac{A_d}{A_e} \tag{1}$$

$$C_{dsi} = C_{ds} \cdot \frac{A_e - A_d}{A_e} \tag{2}$$

where S_e is the total surface of the electrode (9 cm^2) and S_d the surface of the discharge measured from the image of the discharge. The Figure 3 presents a result of this calculation for a N_2 concentration of 0.8% (Figure 1 (d), S_d=3,8 cm^2).

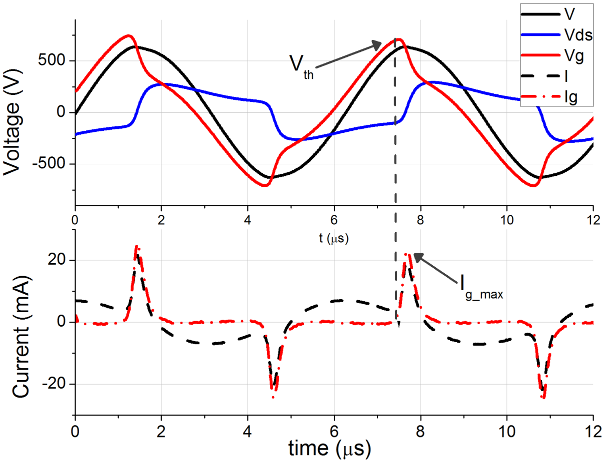

Figure 3: Time evolution of the currents and the voltage

This calculation allows can be used to identify the ignition voltage V_{th} and the maximum current of the discharge I_{g_max}.

3 Results

The nitrogen proportion is increased (starting from pure helium) in order to see the transition between different stages of discharge.

At low concentration of helium (Figure 1 (a) and (b)), discharge is diffuse and spread over the whole surface of the electrode. When N_2 concentration increases the area of the discharge decreases, but the discharge is always more or less diffuse (Figure 1 (c) and (d)). For one concentration the area of the discharge is always the same from one cycle to another, but the location move slowly: i.e this displacement with any rules is visible to the naked eye. Increasing again the amount of nitrogen, some filament appears but the major part of the discharge seems homogenous ((Figure 1 (d) and (e)). This filament appears preferentially at the exit of the DBD. When N_2 concentration reaches 1 %, keeping the gas flow rates constant, and looking to several periods, discharge may contain only filaments (as presented in Figure 1 (f)) or may contain a diffuse part (as presented in Figure 1 (e)). The discharge is unsteady, a series of tightening / relaxation being observed. Next, when N_2 concentration is higher than 1.1% the homogenous part of the discharge disappears suddenly, and discharge consist on filaments at the exit of the DBD. These 1.2 mm^2 filaments are regularly spaced of 2 mm. A time evolution of the discharge (not shown here) indicates that each filament ignites simultaneously. Filaments are located on a "line" at the exit of the DBD, but not exactly at the same position. The displacement of the filament is visible at the naked eye, which indicates than a slow process governs this movement.

Also, for all the nitrogen concentration, discharge stays always clearly visible between two ignitions (not shown here): this suggests that these discharges are not ignited by streamers.

3.1 Surface modification in diffuse mode

As it can be seen on Figure 4, ignition voltage increased with nitrogen concentration this is consistent with the Pashen theory, breakdown voltage being higher for nitrogen than for helium.. The modification of the ignition voltage tends to increase the voltage of the power supply or to shift the time of the ignition. In any case the impedance of the discharge and so the external impedance of the power supply is mismatched.

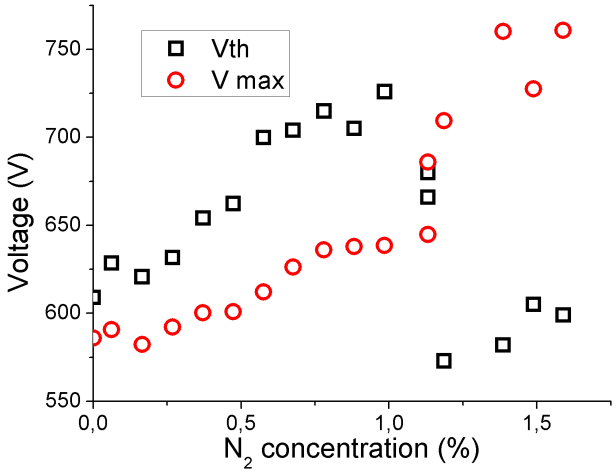

Figure 4: Voltage ignition of the discharge V_{th}, and maximum voltage of the DBD V_{max}

Power supply being regulated in power, when the impedance of the discharge is modified, the reflected power increase and active power diminished: thus current injected in the discharge decreases. As seen on Figure 5, the maximum current density in diffuse mode is nearly constant (around 5mA/cm^2) or increases very slightly. In this condition a diminution of the current implies logically a diminution of the area of the discharge. To sustain this diffuse discharge, the maximum current density could probably not fall bellow a threshold value.

In Figure 5, specials cases corresponding to the transition mode (when discharge contains both a diffuse part and several filaments, like on Figure 1 (e)) are marked by cross. For these conditions, currents densities J are calculated using both LF and HF. The HF selects only the area of the filaments:

thus J calculated with HF is higher than J calculated with LF, so when N_2 concentration reaches 1%, the local maximum current density increases significantly where filaments appear.

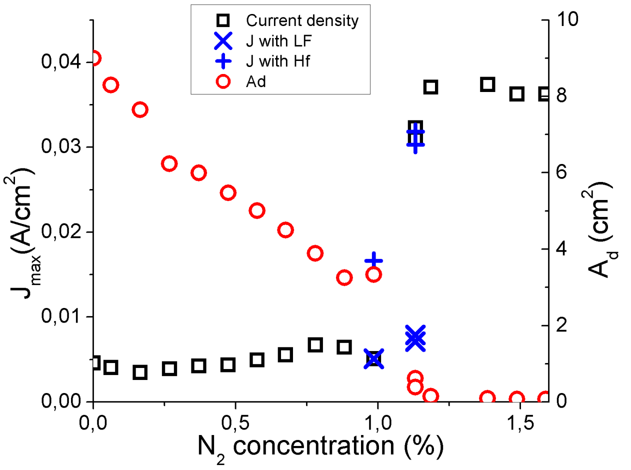

Figure 5: Maximum current density and area of the discharge versus nitrogen concentration

3.2 Filament mode and influence of the surface

For highest nitrogen concentrations, the discharge contains only a few filaments, and the total current of the discharge is equal to a few mA. In this condition the power supply is completely mismatched and the power transferred to the discharge is not measurable with a good accuracy. When N_2 concentration increases the number of filaments diminishes. Figure 4 shows that voltage breakdown drops by almost 150V after the transition to filament mode. It suggests that a memory effect favoured the ignition of the discharge. Memory effect may arise from exited species, light being still slightly visible at filament position between two discharges. However it cannot explain this huge diminution of the breakdown voltage, because in diffuse mode light is also visible between two successive discharges.

As shown in Figure 5, even if the total current tends to decrease, the current density is about ten times higher than in diffuse mode. In this condition the electric charge locally stored on the dielectric at the discharge position is thus more important than in diffuse mode. According to [11] this charge also favoured the ignition of the discharge. As we can see in the transition mode (Figure 1 (d) and (e)), filament appears preferentially at the exit of the DBD. So during this phase, the charge density deposited on the dielectrics is more important at these positions. As soon as discharge becomes only filamentary, ignition is then favoured at the exit of the DBD. Therefore the memory effect is certainly due not only to excited species in the gas but also to charge deposited on the dielectrics, especially in the filamentary mode.

4 Conclusion

Adding of nitrogen in a helium APGD sustained at high frequency (150kHz) tends to perturb the discharge uniformity which transits to a pattern made of filaments equally distributed at the exit of the DBD. For the lowest N_2 concentrations, discharge is diffuse, the current density is constant and rather low (< 100 mA/cm^2). Adding of small amount of nitrogen (< 1%) increases the ignition voltage, which tends to mismatch the power supply and then to reduce the injected power. As a result, the total discharge current decreases, and thus the surface of the discharge is reduced. Afterwards, a few filaments appear and above a threshold concentration (around 1.1%) only a few filaments are localized at the exit of the DBD: ignition voltage drops and current density increases strongly (> 30 mA/cm^2). In this mode, it seems that the local charge deposited on the dielectric by previous discharge play a major part on the sustaining of the discharge.

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