Collective phenomena in volume and surface barrier discharges

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Abstract. Barrier discharges are increasingly used as a cost-effective configuration to produce non-equilibrium plasmas at atmospheric pressure. This way, copious amounts of electrons, ions, free radicals and excited species can be generated without significant heating of the background gas. In most applications the barrier is made of dielectric material. Major applications utilizing mainly dielectric barriers include ozone generation, surface cleaning and modification, polymer and textile treatment, sterilization, pollution control, CO\textsubscript{2} lasers, excimer lamps, plasma display panels (flat TV screens). More recent research efforts are devoted to biomedical applications and to plasma actuators for flow control. Sinusoidal feeding voltages at various frequencies as well as pulsed excitation schemes are used. Volume as well as surface barrier discharges can exist in the form of filamentary, regularly patterned or diffuse, laterally homogeneous discharges. The physical effects leading to collective phenomena in volume and surface barrier discharges are discussed in detail. Special attention is paid to self-organization of current filaments and pattern formation. Major similarities of the two types of barrier discharges are elaborated.

1. Introduction
Gas discharges, predominantly used at atmospheric pressure and formed in narrow gaps between closely spaced electrodes, at least one of which is covered by a special coating are called barrier discharges (BDs). Typical barrier materials used are thin glass or ceramic plates or tubes. In laboratory experiments also the use of resistive, ferroelectric and semiconducting materials has been investigated. Also the use of porous ceramic layers and dielectric barriers with controlled surface conductivity has been reported. By far the most important BDs are those using dielectric barriers: dielectric barrier discharges or DBDs, in the literature also often referred to as silent discharges. Due to better diagnostics, advanced computer simulations and novel applications DBDs, known since 1857, have experienced a genuine renaissance during the past two decades. Reviews of the subject and of the older literature on barrier discharges were published by Kogelschatz et al [1], by Wagner et al [2] and by Fridman et al [3]. A detailed discussion of various properties of barrier discharges and their important industrial applications can also be found in the book *Non-Equilibrium Air Plasmas at Atmospheric Pressure* by Becker et al [4]. More recent research activities focus on DBD torches [5], on flow control [6] and on biomedical applications [7]. In this contribution the focus is on the discharge physics, mainly on collective phenomena such as filamentation, pattern formation and self-organization, and on the conditions for obtaining diffuse, laterally homogeneous discharges.

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2. Volume barrier discharges (VBDs)

2.1 Filamentary VBDs

In many atmospheric-pressure VBDs a multitude of thin current filaments referred to as microdischarges (MDs) is observed. The duration of a single microdischarge is a few ns, the transferred charge is of the order 0.1 nC for a 1 mm air gap, increasing with gap spacing and specific capacitance of the dielectric barrier(s). Although previously it had been assumed that these MDs are randomly distributed in space and time we now know that they occur only during certain phases of the discharge cycle and that there is quite a bit of spatial coordination and self-organization of MDs [8]. The charge deposited by a MD at the dielectric surface determines its duration by reducing the electric field in the gap at this location. It also has an influence on adjacent or subsequent MDs. As long as the voltage is rising new MDs occur in new locations where the electric field is still high. When the voltage reverses the next MDs preferentially seek locations of previous MDs where the field has collapsed. This memory effect caused by the surface charges deposited on the dielectric is extensively used in plasma displays [9]. At elevated frequencies additional volume memory effects are observed when the time between succeeding half cycles becomes too short for the ions or electrons to decay or be swept out of the gap. Also long-lived metastables can carry information from the previous half cycle.

Since all MDs are initiated at about the same breakdown voltage and the overall gap voltage stays close to the breakdown value during the active discharge phase a rather simple equivalent circuit for such an ensemble of a large number of MDs can be given (figure 1a). The discharge gap is represented by two anti-parallel Zener diodes, clamping the gap voltage at the breakdown value. In this case the voltage-charge Lissajous figure of the DBD resembles an ideal parallelogram (figure 1b) in which the slopes of the straight lines are related to the total capacitance of the configuration during the phases without discharge and to the capacitance of the dielectric barrier(s) during the active phases. The voltage change due to the charge transfer of a single MD is less than the line width in the diagram. Under certain conditions pronounced voltage collapses are observed that are indicative of simultaneous discharge of a large number of MDs covering a considerable fraction of the electrode area (figure 1c). The diagrams were obtained with a laboratory ozone generator with a 1 mm wide annular discharge gap formed by an outer steel tube and an inner glass tube of 1 m length (sinusoidal feeding voltage, frequency: 1 kHz, electrode area: 1200 cm²).

![Figure 1](image-url) Figure 1. Simple equivalent circuit and voltage-charge Lissajous figures of a filamentary DBD in O₂ without and with self-pulsing.

This self-pulsing of the discharge has also been observed in mixtures CO₂ and CH₄ [10]. It depends on the slope dU/dt of the feeding voltage when the breakdown voltage in the gap is reached and on the surface conditions. They are influenced by humidity (surface conductivity) and also by deposition on or etching of the surface. Pulsing effects can occur only during the positive half cycle, only during the negative half cycle, or in both. The reason for this behaviour is that during the delay phase of breakdown the radiation of one initial MD can trigger adjacent MDs through the action of UV photons releasing electrons from the electrode surfaces. In the case of fast rising voltages (pulsed DBDs) the MDs can be synchronized in such a way that the entire gap voltage collapses in a short time.
2.2 Single filament measurements

The last decade, by the use of advanced diagnostic techniques, brought much more detailed information about the plasma parameters inside the MD columns. Different groups succeeded in stabilizing the location of an individual current filament so that repetitive measurement techniques could be applied. Probably the most powerful tool is cross-correlation spectroscopy (CCS), first introduced to DBD investigations by Kozlov and co-workers at Moscow State University in 1995, described in detail in 2001 [11] and more recently reviewed in a book chapter by Wagner et al [12]. CCS allows sensitive emission spectroscopy with high spatial and temporal resolution. Such measurements provided important data about the local and temporal evolution of the electric field and the relative electron density inside a MD channel and led to a better understanding of the electrical breakdown processes leading to MD formation, the discharge physics as well as the involved plasma chemistry. Subsequent investigations were extended to rare gases and diffuse barrier discharges. Other groups focused on the kinetics of excimer formation and on the quantitative evaluation of VUV excimer radiation in Ar and Xe [13]. Perhaps a remark of caution should be added. An isolated single MD filament may not have exactly the same properties as a MD squeezed in between adjacent MDs and forced to share the available surface area and dielectric capacitance with its neighbours.

2.3 Single filament modelling

Early 2D numerical simulations of MD formation [14] showed that after an initial electron avalanche phase an ionisation wave is formed that upon arrival at the momentary cathode results in the formation of a thin cathode fall region of high electric field strength. In air, O$_2$ or N$_2$ at atmospheric pressure this fall region extends only a few $\mu$m into the discharge gap. The current peak of a single MD follows the formation of the cathode fall. Immediately thereafter charge accumulation on the dielectric leads to a reduction of the electric field at this location until the MD is extinguished. Consequently a MD can be regarded as a self-arresting discharge of a few ns duration. More advanced numerical models were published for atmospheric pressure air [15] and N$_2$ [16]. Computed emission intensities of the second positive and the first negative systems of nitrogen agree with recent experimental data. Experimental results for a relatively long (up to 1 $\mu$s) Townsend pre-phase and for the velocity of the cathode-directed ionizing wave are satisfactorily reproduced in the models. Secondary electron emission from the dielectric surface caused by impinging ions on the momentary cathode is an important process. Inside the MD channel electron densities of the order $10^{14}$ cm$^{-3}$ are reached. At the dielectric the MD channel spreads into a wider surface discharge. With its thin high field region (reduced field E/n about 1000 Td) at the momentary cathode and a channel of quasi-neutral plasma (positive column) at relatively low reduced field (E/n about 100 Td) each MD in its high current phase can be characterized as a transient high pressure glow discharge. In these models the cathode layer on the dielectric is formed as an extremely thin (5 - 10 $\mu$m thick) space charge layer. Both modelling efforts come to the conclusion that photon-induced volume processes (photoionisation) must be considered to adequately describe the expansion of the MD channel across the surface of the cathode dielectric during the MD quenching phase.

2.4 Pattern formation in VBDs

Under certain conditions the weakly ionized plasma in a DBD can also show regular self-organized luminous patterns. Many authors described the formation of luminous spots and regular discharge patterns in barrier discharges between narrowly spaced planar electrodes [17]. Boyers and Tiller described hexagonal arrays of “plasma bubble domains” which they identified as regular patterns of localized glow discharges. They already distinguished between dim uniform Townsend discharges, assemblies of glow discharge domains and bright uniform normal or abnormal glow discharges. Kogelschatz showed a hexagonal DBD discharge pattern resembling Rayleigh-Bénard convection cells (figure 2c). Breazeal and co-workers talked about static and dynamic two-dimensional current-density patterns of “self-extinguishing discharge avalanches” [17].
Figure 2. Two-dimensional discharge patterns obtained in 5-mm wide cell with planar walls filled with xenon/chlorine mixtures at different pressures (visible diameter: 8 cm, 1 kHz sine voltage).

Figure 2 shows photographs of self-organized discharge structures taken in 1991. A round flat silica glass cell of 5 mm width with planar walls was filled with Xe/Cl₂ mixtures at different pressures. The walls served as dielectric barriers. These photographs were taken with a normal camera and relatively long exposure times (20 ms) indicating fairly stationary conditions. The picture in the middle clearly shows discharge areas of different luminosity and presumably different current density with intermediate dark regions. Very beautiful discharge patterns including spirals, hexagonal and square lattice and interlacing superlattice patterns have been published by Lifang Dong and co-workers [18]. They used Ar and Ar/air mixtures in a relatively simple DBD arrangement with planar glass plates as dielectric barriers and water electrodes. Most experiments were performed close to atmospheric pressure with 1.4 mm or 1.5 mm discharge gaps and a sinusoidal feeding voltage with frequencies ranging from 49 to 62 kHz. Figure 3 is taken from their 2008 publication.

Figure 3. Regular patterns in a DBD operating in Ar/air mixtures. Taken from [18c] with permission. © 2008 IEEE

Progress in the understanding of these DBD patterns was made by synchronizing short exposure image converter pictures with current traces and spectroscopic diagnostics. Mirałaï et al [19] presented a systematic investigation of the optical appearance of DBDs in air, He, Ar and N₂. In air they always obtained a filamentary discharge, in He and pure N₂ patterns of luminous columns or totally diffuse discharges, in Ar bright luminous columns which were narrower and more densely packed. At low driving frequency (4 kHz) also in Ar diffuse discharges could be obtained, using a MgO coating on the steel electrode. Gurevich et al [20] reported on the spatio-temporal evolution of luminous patterns in the form of concentric rings (figure 4). In N₂ at a pressure of 2.5 hPa after ignition they first observed
a concentric ring pattern with a bright spot at the centre in the positive half cycle of the operating voltage. When the voltage was further raised they got an inverse pattern with a dark spot at the centre and dark regions at the position of the previously bright rings. Changing to the negative half cycle they first obtained the ring pattern with the dark centre followed by the pattern with the bright spot at the centre. The two ring patterns per half cycle corresponded to two current peaks per half cycle superimposed on the sinusoidal displacement current. This is a clear indication that the spatiotemporal behaviour of the ring pattern is determined by the charges previously deposited on the glass plates.

Figure 4. Concentric ring patterns in a DBD in N₂. Reprinted with permission from Gurevich E L, Zanin A L, Moskalenko A S and Purwins H-G Phys. Rev. Lett. 91, 154501, 2003. Copyright (2003) by the American Physical Society. http://prl.aps.org/abstract/PRL/v91/i15/e154501

Bernecker et al [21] observed a similar spatiotemporal behaviour with hexagonal luminous structures in Ne. At the beginning of a cycle first a bright luminous hexagonal structure appeared, followed by a much fainter honeycomb structure in the space between. These two interlacing structures are related to a first high current peak and to a much smaller current peak during one half cycle of the driving voltage. The authors suggest that the bright regions can be characterized as glow-discharge domains while the darker regions in between are diffuse Townsend discharges. The type of pattern obtained in a DBD depends on the gas properties, the width of the discharge gap and the operating pressure, but also on the barrier thickness and material and on the driving frequency. Also the shape of the electrodes has a strong influence by setting strong boundary conditions [22].

In recent years it became possible to measure localized remnant surface charges in DBDs and to demonstrate that they correspond to observed self-organized luminous glow patterns [23]. Moreover, the experimental results of the surface-charge distribution measurements are in good agreement with those calculated in a full 3D discharge simulation solving the corresponding transport equations [24].

2.5 Modelling of pattern formation in VBDs

Purwins and co-workers presented a number of papers on pattern formation in gas discharges and used phenomenological two or three component activator-inhibitor models (reaction diffusion models) to reproduce the observed luminous patterns [25]. A variety of self-organized patterns could be generated without using details about gas discharge physics. In this approach the gas discharge is treated as a homogeneous medium with S-shaped current-voltage characteristic that contains a section with negative differential conductivity. Ebert and Arrayáys [26] published a more general approach to pattern formation in low current density electrical discharges based on a minimal model of reaction, drift and diffusion of two charged species coupled nonlinearly to an externally imposed electric field. Further details on the transition from Townsend to glow discharge were published by Šijačič and Ebert [27] and by Raizer et al [28].

Brauer et al [29] used a self-consistent two-dimensional fluid model of a He DBD (2.4·10⁴ Pa, 0.5 mm gap). The authors could show how an initially homogeneous plasma abruptly turned into regularly spaced glow discharge regions after about 30 μs, which corresponded to 6 cycles of the applied sinusoidal voltage. Zhang and Kortshagen [30], using a more complex kinetic model for He including
20 ppm N₂, showed that also the opposite can occur. A patterned He DBD can transit to a transversely homogeneous discharge. In conclusion, it can be stated that the self-organized behaviour of DBDs can be simulated by phenomenological activator-inhibitor models or, more precisely, by 2D or 3D models treating the discharge physics and chemical kinetics. The latter are also able to predict the size and the spacing of the glow discharge regions found in experiments. Also the time it takes to reach stationary conditions is reproduced in the simulations. An increase in pressure leads to smaller glow domains and closer spacing, in experiment as well as in simulation.

2.6 Diffuse volume barrier discharges
Early experimental work on diffuse or laterally homogeneous DBDs at atmospheric pressure was initiated by Okazaki and co-workers at Sophia University in Tokyo about 1987 [31] and followed up by Massines and her group in Toulouse [32]. This work started a world wide activity in the field. Recent advances have been reviewed by Massines et al [33]. In the beginning, all diffuse DBDs were referred to as atmospheric pressure glow discharges (APGs, APGDs). Later one learned to distinguish between glow discharges and more Townsend-like discharges (APTds). It is relatively easy to obtain homogeneous DBDs in He, Ne or N₂. With additives or a special sandwich structure placing a wire mesh between the dielectric and the metal electrode also in air, O₂ and Ar stable glows were obtained in atmospheric pressure DBDs, even when using a 50 Hz source [34]. These experiments were repeated and confirmed by many groups [35]. The function of the wire mesh at the back side of the dielectric remained a mystery for a long time. Through the work of Tepper [36] and that of Fang [35] it was clarified that the mesh initiates a corona discharge that evenly charges the PET (polyethyleneterephthalate) dielectric, which is an electret material. When a certain threshold voltage is reached charge carriers are spontaneously expelled into the main gas gap (polarization switching).

More detailed information about homogeneous DBDs and transitions between diffuse and filamentary DBDs were obtained by advanced diagnostics using short exposure ICCD images and spectroscopy (CCS, LIF) linked to electrical measurements [37]. The existence and extension of a high field region at the cathode in the case of He discharges was confirmed by Stark effect measurements [38]. The measured values of the electric field near the cathode (about 10 kV/cm) and the extension of the cathode fall region (about 0.6 mm) indicate that these DBD glow discharges do not reach the state of a fully developed glow discharge. From atmospheric pressure DC glow discharges in He between metal electrodes the following experimental results were reported: current density at cathode 2.3 A/cm², electric field at cathode: 62 kV/cm, width of cathode layer: 0.06 mm [39]. A reduction of the current density reduces the field strength and increases the extension of the fall region [40]. It appears that in most DBDs the dielectric barrier quenches the discharge at an early stage of cathode fall development already at a peak current density of a few mA/cm².

From the large number of publications on homogeneous DBDs one must conclude that many parameters including the properties of the power supply, the dielectric barriers, the used gas and pressure, the geometrical configuration and, most strikingly, the operating frequency have an influence. Memory effects including surface charges and long living species from the previous half cycle play a dominant role. For this reason the first few cycles after ignition differ significantly from the final quasi-stationary state, which normally is achieved within less than 10 cycles. In the first cycles filaments and moving current fronts are observed. Nevertheless it is possible to specify working domains in which homogeneous DBDs can be reproducibly obtained. Most homogeneous DBDs are characterized by one short current pulse per half cycle of the operating voltage. An interesting alternative is the multi pulse mode in which a number of regularly spaced short current pulsed of descending peak height are obtained per half cycle [41]. Very recently it was demonstrated that a fast gas flow can influence the number of pulses and also the shape of the short current pulses [42].

2.7 Numerical modelling of diffuse VBDs
A few remarks concerning the terms used in the literature should be made. The diffuse or “homogeneous” DBD described in many papers is at best transversely or laterally homogeneous. In
the direction of the electric field it is never homogeneous. Many authors distinguish between glow discharge DBDs and Townsend-like DBDs. These expressions are borrowed from low pressure dc discharges. A glow discharge is characterized by a high field region at the cathode (cathode fall region), a region of negative glow and a column of quasi-neutral plasma (positive column) in addition to intermediate dark spaces. A classical Townsend discharge is characterized by electron and ion concentrations small enough not to noticeably distort the applied electric field. Both, over a wide range, maintain a voltage independent of the current. In the extensive literature on DBDs the terms are used in a less stringent form. Apparently homogeneous DBDs with a high field region near the momentary cathode, indicative of a cathode fall region, are called glow or glow-like DBDs. Uniform barrier discharges in the Townsend regime are frequently characterized by much lower current densities and by the absence of a quasi-neutral plasma region. In diffuse DBDs we often observe operating modes in which the cathode fall is not fully developed due to the current limitation by the dielectric barriers but space charge concentrations are too high to qualify as classical Townsend discharges. For this intermediate range the qualification subnormal glow discharge is sometimes used.

A large number of papers deal with the numerical modelling of homogeneous He DBDs at atmospheric pressure. Contrary to low pressure discharges, molecular species in the form of the excited dimer He2\(^+\) and the ion He2\(^+\) now gain importance [43]. The influence of impurities in rare gas plasmas is stressed [44,45]. Even a minute 1 ppm N\(_2\) admixture to pure He will make N\(_2^+\) ions as abundant as He2\(^+\) ions. Above 17 ppm admixture nitrogen ions govern the positive charge carriers and N\(_2^+\) takes a leading role [45]. Excited He species in connection with impurities play an important role in sustaining a diffuse discharge. A detailed numerical model of such a discharge in a 5mm gap between glass plates operated at 35 kHz shows a short current pulse of sub-microsecond duration per half cycle, a high field region at the cathode indicating the structure of a glow discharge at maximum current density (2.3 mA cm\(^{-2}\)) and resembling the structure of a subnormal glow discharge with residual electrons at the momentary anode just before the next current peak [46]. These results are in excellent agreement with measurements by Luo et al [47]. Also the appearance of a multitude of short current pulses per half cycle observed when the voltage is raised could be explained by modelling [48]. By varying the thickness of the dielectric Mangolini et al could demonstrate its current limiting properties [49]. A thicker dielectric reduces the observed current peak and shifts the operating point along the subnormal branch of the current voltage characteristic from a glow-like towards a more Townsend-like appearance. Detailed 2D models [30] could also reproduce observed radially moving current fronts during the ignition phase [50] and transitions from an initially filamentary to a diffuse discharge. This can be achieved by increasing the operating frequency or the applied voltage or by decreasing the permittivity of the dielectric. In the first case more luminous regions appear and coalesce to form a transversely uniform glow discharge. In the second case, lowering the permittivity, the number density decreases and finally results in a transversely uniform Townsend discharge. Penning ionisation by metastables, secondary electron emission induced by ions and metastables and remnant surface charges have a large influence.

Most authors treating homogeneous DBDs in nitrogen at atmospheric pressure come to the conclusion that this discharge in fact has many similarities with a Townsend discharge [51]. The observed current pulse is much longer (about 30-90 µs) than in He and the peak current density is lower by at least an order of magnitude (typically 0.1 – 0.3 mA cm\(^{-3}\)). The evolution of a N\(_2\) DBD at 130 kHz was investigated by Panousis et al in a coupled electro-dynamic and kinetic model [52]. Most modellers succeed in approximating measured current and voltage traces. The long living metastable triplet state N\(_2\)(\(\Lambda^3\Sigma_u^+)\) plays an important role. When efficient quenchers of this species like O\(_2\) or NO are added the discharge behaviour changes dramatically [53]. Also Townsend-like DBDs can exhibit multipulse behaviour with several short current pulses per half cycle for which also an analytical model was proposed [54]. Stability analysis suggests that Townsend discharges are more stable against lateral perturbations than glow discharges [27,55]. In their numerical simulation of the short high-current pulses obtained by polarization switching Golubovskii and co-workers come to the conclusion that under these conditions the nitrogen Townsend discharge changes into a glow mode [56].
3. Surface barrier discharges (SBDs)
Like volume barrier discharges also surface barrier discharges (SBDs) have a long history. First applications for boxer chargers in electrostatic precipitators and for ozone generators were proposed by Masuda et al. [57]. They used rows of parallel open HV electrodes separated from the ground electrode by a thin dielectric layer (figure 5b).

![Figure 5. Examples of surface barrier discharge configurations (SBDs).](image)

Based on Masuda’s ideas different electrode configurations have been investigated (figure 5). The most prominent is the coplanar barrier discharge (CBD) used in plasma displays with rows of parallel linear electrodes buried in or covered by dielectric material (figure 5c) [9]. This large-volume application and the more recent prospect of using SBD plasma actuators for flow control have stimulated substantial research activities. Devices intended for flow control normally use one open electrode and another one slightly displaced and buried inside or below dielectric material (figure 5d).

![Figure 6. Manifestations of surface discharges (SBDs) taken from [58, 62a, 59] with permission.](image)

Figure 6a, taken from the dissertation of Katia Allégraud [58], shows an ICCD image of a surface discharge in Ar (exposure time: 100 ns, taken 200 ns after streamer ignition). Figure 6b is a dust figure of a surface discharge in air of a linear electrode and figure 6c shows photographs of a section of a large-area electrode configuration (22 cm by 14 cm) [59]. The gas discharge is always initiated in the inhomogeneous field at or close to the edge of one electrode and moves along the dielectric surface as a surface discharge (creeping discharge, sliding discharge). In atmospheric pressure air the discharge consists of bright filaments during the positive half-period of the applied voltage [60]. During the negative half-period the emission is weaker and more diffuse. Many experiments were conducted in ambient air. Traces of the current filaments can be documented by dust figures, originally proposed by Lichtenberg in 1777 [61], by photographic Lichtenberg figures, by charge measurements and, more recently, by fast imaging techniques, now reaching gating times of sub-nanosecond duration. The structured charge arrangement covers an area that increases with time and voltage amplitude. A stepwise propagation is observed caused by a repeated re-ignition of the current channels, sometimes referred to as surface streamers. The thin filaments have currents and transported charges similar to those found in microdischarges in VBDs [62]. At peak current a quasi-neutral plasma with electron densities of the order $10^{14}$ cm$^{-3}$ is established after formation of a thin cathode layer near the negative electrode, even in the case it is covered by a dielectric layer. The charge deposited on the dielectric surface reduces the electric field in the filament and finally chokes the current flow. In addition to the barrier thickness and permittivity also the barrier structure and its chemical composition define the...
discharge characteristics and its structure [63]. Charge-voltage Lissajous figures resemble those of volume DBDs [60]. Some authors using CBDs reported that in nitrogen and ambient air at high power densities (100 W/cm\(^2\)) the discharge turns into a “visually almost uniform plasma” [64]. They called it a diffuse coplanar surface dielectric barrier discharge (DCSD, DCSBD). From the diagnostics presented it is not clear whether this discharge is really homogeneous or a very close spacing of filaments. Earlier investigations on SBDs in He came to the conclusion that under certain conditions diffuse discharges can be obtained [65]. The conclusion was that, similar to the experience with volume DBDs, remaining metastables and free electrons from the previous half cycle play a crucial role.

In some experiments a striking synchronization of current filaments in SDs was reported [60, 66]. Kashiwagi and Itoh investigated this effect in detail and showed that UV radiation from the first filament was responsible for triggering adjacent filaments. In air at atmospheric pressure the most effective spectral range was about 115 nm in the vacuum UV and reached for a distance of 120 mm. These photons of 10 eV energy fall into an absorption window of oxygen and are capable of releasing secondary electrons from dielectric surfaces or photoionising NO, which is rapidly formed in N\(_2\)/O\(_2\) mixtures. Numerical simulations of the dynamic behaviour of surface streamers by Tanaka et al [67] showed that the experimental results can only be reproduced when photoelectron emission and volume photoionisation are taken into consideration.

**Figure 7.** Coplanar surface DBD with embedded needle electrodes. b) side view, c) top view. Taken from [69] with permission.

More recent simulations of the surface current filaments in O\(_2\) and in air present more details about the propagation and the thickness of the surface discharges [68]. Experimental values for the length of the filaments and the charge density on the dielectric can now be adequately simulated. An interesting detail is the prediction that the streamer head starting from a positive electrode travels at a height of 0.05 cm above the dielectric surface. This is in agreement with recent short exposure CCD images by Hoder \textit{et al} [69] showing that the surface discharge is located slightly above the surface. It maybe of interest to note that well arranged equally spaced SBDs reminiscent of pattern formation in VBDs have been observed [70]. In certain electrode configurations also phases of diffuse SBDs have been theoretically predicted and recently also found experimentally [71].

**4. Conclusions**

It can be concluded that the plasma properties obtained in VBDs and SBS are similar. Filamentation, pattern formation and diffuse appearance have been observed in both. Collective effects caused by UV photons and remnant surface charges play a crucial role. The overall discharge behaviour is dominated by the current limiting properties of the dielectric barrier. Current densities can vary by several orders of magnitude and cover the full range of Townsend-like discharges to atmospheric pressure glow discharges. The VBD type that comes closest to the values expected from similarity laws is the filamentary discharge observed in atmospheric pressure in O\(_2\), N\(_2\) or air. In these filaments the current density in the quasi-neutral column and the properties of the cathode fall region correspond to those expected for atmospheric pressure glow discharges.

Numerical modelling has been very successful in providing new insight into the chemical kinetics, the influence of impurities and the distribution of charges in the discharge gap. One of the major results is that plasma chemistry substantially influences electrical discharge behaviour. Nevertheless
there is still considerable debate on individual processes involved, especially at the surfaces. It is still an open question how previously stored electrons or ions are released from or neutralized at a dielectric surface. Spontaneous or thermal electron desorption and secondary electron emission induced by impinging ions, metastables and UV photons are among the processes suggested. In many models rather arbitrary assumptions about the coefficients for secondary electron release from dielectric surfaces had to be introduced to match experimental data. Further research is needed about the physisorption kinetics of charged particles at dielectric boundaries to find out how electron-ion recombination, transverse charge motion and secondary electron emission is effected.

References

[1] Kogelschatz U, Eliasson B and Egli W 1999 Pure Appl. Chem. 71 1819-28; Kogelschatz U 2002 IEEE Trans. Plasma Sci. 30 1400-8; 2003 Plasma Chem. Plasma Process. 23 1-46
[2] Wagner H-E, Brandenburg R, Kozlov K V, Sonnenfeld A, Michel P and Behnke J F 2003 Vacuum 71 417-36
[3] Fridman A, Chirokov A and Gutsol A 2005 J. Phys. D: Appl. Phys. 38 R1-24
[4] Becker K H, Kogelschatz U, Schoenbach K H and Barker R J eds 2004 Non-Equilibrium Air Plasmas at Atmospheric Pressure (Bristol and Philadelphia: IOP)
[5] Laroussi M and Akan T 2007 Plasma Proc. Polym. 4 777-88
[6] Moreau E 2007 J. Phys. D: Appl. Phys. 40 605-36; Corke T C, Post M L and Orlof D M 2009 Exp. Fluids 46 1-26; Miles R B, Opatis D F, Shneider M N, Zaidi S H and Macheret S O 2009 Eur. Phys. J. Appl. Phys. 47 22802
[7] Fridman G, Friedman G, Gutsol A, Shekhter A B, Vasilets V N and Fridman A 2008 Plasma Process. Polym. 5 503-33; Dobrynin D, Fridman G, Friedman G and Fridman A 2009 New J. Phys. 11 115020; Laroussi M 2009 IEEE Trans. Plasma Sci. 37 714-25
[8] Chirokov A, Gutsol A, Fridman A, Sieber K D, Grace J M and Robinson K S 2004 Plasma Sources Sci. Technol. 13 623-35; 2005 IEEE Trans. Plasma Sci. 33 300-1
[9] BOEUF J-P 2003 J. Phys. D: Appl Phys. 36 R53-79
[10] Kozlov K V, Michel P and Wagner H-E 2000 Plasmas Polym. 5 129-49
[11] Kozlov K V, Wagner H-E, Brandenburg R and Michel P 2001 J. Phys. D: Appl. Phys. 34 3164-76
[12] Wagner H-E, Kozlov K V and Brandenburg R 2008 Cross-correlation emission spectroscopy in Low Temperature Plasmas vol 1 ed R Hippler et al (Weinhein: WILEY-VCH) chapter 10 pp 271-306
[13] Merbahi N, Sewraj N, Marchal F, Salamero Y and Millet P 2004 J. Phys. D: Appl. Phys. 37 1664-78; Merbahi N, Ledru G, Sewraj N and Marchal F 2007 J. Appl. Phys. 101 123309; Sewraj N, Merbahi N, Marchal F, Ledru G and Gardou J-P 2009 J. Phys. D: Appl. Phys. 42 045206
[14] Eliasson B and Kogelschatz U 1991 IEEE Trans. Plasma Sci. 19 309-22; Braun D, Gibalov V and Pietsch G 1992 Plasma Sources Sci. Technol. 1 166-72; Li J and Dhali S K 1997 J. Appl. Phys. 82 4205-10; Steinle G, Neundorf D, Hiller W and Pietralla M 1999 J. Phys. D: Appl. Phys. 32 1350-6; Gibalov V I and Pietsch G J 2000 J. Phys. D: Appl. Phys. 33 2618-36
[15] Yurgelenas Yu V and Wagner H-E 2006 J. Phys. D: Appl. Phys. 39 4031-43; Yurgelenas Yu V and Leeva M A 2009 IEEE Trans. Plasma Sci. 37 809-15
[16] Papageorgiou L, Panousis E, Loiseau J F, Spyrou N and Held B 2009 J. Phys. D: Appl. Phys. 42 105201
[17] Boyers D G and Tiller W A 1982 Appl. Phys. Lett. 41 28–30; Kogelschatz U 1992 Silent discharges and their applications in Proc. 10th Int. Conf. on Gas Discharges and their Applications (Swansea, UK, 13-18 September 1992) vol 2 ed W T Williams pp 972-80; Breazeal W, Flynn K M and Gwinn E G 1995 Phys. Rev. E 52 1503-15
[18] Dong L, Yin Z, Wang L, Fu G, He Y, Chai Z and Li X 2003 Thin Solid Films 435 120-3; Dong L, Yin Z, Li X, Chai Z and He Y 2006 Plasma Sources Sci. Technol. 15 840-4; Dong, L, Fan W, He Y and Liu F 2008 IEEE Trans. Plasma Sci. 36 1356-7
[19] MirlaI S F, Czeremuszkin G and Wertheimer M R 2000 High speed camera imaging of dielectric barrier discharges in He, Ar, N2 and air in Proc. 7th Int. Symp. on High Pressure Low Temperature Plasma Chemistry (Greifswald, Germany, 10-13 September 2000) vol 1 ed H-E Wagner et al pp 33-7
[20] Gurevich E L, Zanin A L, Moskalenko A S and Purwins H-G 2003 Phys. Rev. Lett. 91 154501
[21] Bernecker B, Callegari T, Blanco S, Fournier R and BOEUF J-P 2009 Eur. Phys. J. Appl. Phys. 47 22808
[22] Duan X, Ouyang J, Zhao X and He F 2009 Phys. Rev. E 80 016202.1-5
[23] Stollenwerk L, Laven J G and Purwins H-G 2007 Phys. Rev. Lett. 98 255001; Stollenwerk L 2009 New J.
Massines F, Amiranashvili S, Boeuf J-P and Purwins H-G 2006 *Phys. Rev. Lett.* 96 255001

[24] Stollenwerk L, Amiranashvili S, Boeuf J-P and Purwins H-G 2006 *Phys. Rev. Lett.* 96 255001

[25] Astrov Y, Ammelt E, Teperick S and Purwins H-G 1999 *J. Appl. Phys.* 85 7569-72; Müller I, Punset C, Ammelt E, Purwins H-G and Boeuf J P 1999 IEEE Trans. Plasma Sci. 27 20-1

[26] Astrov Y and Purwins H-G 2001 *Phys. Lett. A* 283 349-54;

[27] Šijačić D D and Ebert U 2002 *Phys. Rev. E* 66 066410

[28] Raizer Yu P, Ebert U and Šijačić D D 2004 *Phys. Rev. E* 70 017401

[29] Braun A, Punset C, Gherardi N, Naudé N and Ségur P 2009 *J. Phys. D: Appl. Phys.* 42 033304; Dilecce G, Ambrico P F and De Benedictis S 2007 *Appl. Phys. Lett.* 91 221504; Dilecce G, Ambrico P F and De Benedictis S 2007 *Appl. Phys. Lett.* 91 221504

[30] Visentin G, Mangolini L, Orlov K, Kortshagen U and Heberlein J 2006 *Plasma Sources Sci. Technol.* 15 845-8; Fang Z, Qiu Y, Zhang C and Kuffel E 2007 *J. Phys. D: Appl. Phys.* 40 1401-7

[31] Tepper J and Lindmayer M 2000 *Investigations on two different kinds of homogeneous barrier discharges at atmospheric pressure in Proc. 7th Int. Symp. on High Pressure Low Temperature Plasma Chemistry* (Greifswald, Germany, 10-13 September 2000) vol 1 ed H-E Wagner et al pp 38-43

[32] Gherardi N and Massines F 2005 *J. Appl. Phys.* 97 22805

[33] Massines F, Gherardi N, Naudé N and Ségur P 2009 *J. Phys. D: Appl. Phys.* 42 085208; J. Phys. D: Appl. Phys. 42 085208;

[34] Gherardi N and Massines F 2005 *J. Phys. D: Appl. Phys.* 38 173-80; Choi J H, Han M H, Baik H K and Song K M 2007 *J. Appl. Phys.* 101 033304; Dilecce G, Ambriico P F and De Benedictis S 2007 *Plasma Sources Sci. Technol.* 16 511-22; Brandenburg R, Navrátíl J, Jánoský J, Stahel P, Truneč D and Wagner H-E 2008 *J. Phys. D: Appl. Phys.* 41 1125-8

[35] Trunček D, Krabec A, Štaňkový F and Bucha J 1998 *Contrib. Plasma Phys.* 38 435-45; Wang X, Luo H, Liang Z, Mao T and Ma R 2006 *Plasma Sources Sci. Technol.* 15 845-8; Fang Z, Qiu Y, Zhang C and Kuffel E 2007 *J. Phys. D: Appl. Phys.* 40 1401-7

[36] Obradović B M, Ivković S S and Kuraica M M 2008 *Appl. Phys. Lett.* 92 191501; Ivković S S, Obradović B M, Cvetanović N, Kuraica M M and Purić J 2009 *J. Phys. D: Appl. Phys.* 42 225206

[37] Wang Q, Koleva L, Donnelly V M and Economou D J 2005 *Appl. Phys. Lett.* 87 1690-7; Arkipenko V I, Kirillov A A, Safronau Ya A, Simonchik L V and Zgirouski S M 2009 *Plasma Sources Sci. Technol.* 18 045013

[38] Gherardi N and Massines F 2005 *J. Phys. D: Appl. Phys.* 38 349-54; *J. Phys. D: Appl. Phys.* 38 349-54

[39] Gherardi N and Massines F 2005 *J. Phys. D: Appl. Phys.* 38 1173-80; Choi J H, Han M H, Baik H K and Song K M 2007 *J. Appl. Phys.* 101 033304; Dilecce G, Ambriico P F and De Benedictis S 2007 *Plasma Sources Sci. Technol.* 16 511-22; Brandenburg R, Navrátíl J, Jánoský J, Stahel P, Truneč D and Wagner H-E 2008 *J. Phys. D: Appl. Phys.* 41 1125-8

[40] Visentin G, Mangolini L, Orlov K, Kortshagen U and Heberlein J 2006 *Plasma Sources Sci. Technol.* 15 845-8; Fang Z, Qiu Y, Zhang C and Kuffel E 2007 *J. Phys. D: Appl. Phys.* 40 1401-7

[41] Reichen P, Sonnenfeld A and Rudolf von Rohr Ph 2010 *J. Phys. D: Appl. Phys.* 43 025207

[42] Kutas K, Hartmann P and Donko Z 2001 *J. Phys. D: Appl. Phys.* 34 3368-77; Wang Y and Wang D 2005 *Phys. Plasmas* 12 023503; Martens T, Bogaerts, A, Brok W and van Dijk J 2007 *Anal. Bioanal. Chem.* 388 1583-94; Martens T, Brok W J M, van Dijk J and Bogaerts A 2010 *Appl. Phys. Lett.* 96 091501

[43] Yuan X and Raja L L 2002 *Appl. Phys. Lett.* 81 814-6

[44] Martens T, Bogaerts, A, Brok W J M and van Dijk J 2008 *Appl. Phys. Lett.* 92 041504

[45] Luo H, Liang Z, Bo L, Wang X, Guan Z and Wang L 2007 *Appl. Phys. Lett.* 91 221504

[46] Akishev Yu S, Demyanov A V, Karalnik V B, Pankin M V and Trustkin N I 2001 *Plasma Phys. Rep.* 27 164-71; Golubovskii Yu B, Maiorov V A, Behnkne J and Behnkne J F 2003 *J. Phys. D: Appl. Phys.* 36 39-49; Yuan X, Shin J and Raja L L 2006 *Vacuum* 80 1199-205; Maiorov V A and Golubovskii Yu B
2007 Plasma Sources Sci. Technol. 16 S67-75; Lü B, Wang X, Luo H-Y and Liang Z 2009 Chinese Phys. B 18 646-51; Zhang Y, Gu B, Wang W, Wang D and Peng X 2009 J. Appl. Phys. 106 023307

[49] Mangolini L, Anderson C, Heberlein J and Kortshagan U 2004 J. Phys. D: Appl. Phys. 37 1021-30

[50] Mangolini L, Orlov K, Kortshagan U, Heberlein J and Kogelschatz U 2002 Appl. Phys. Lett. 80 1722-4; Malik D A, Orlov K E, Miroshnikov I V and Smirnov A S 2005 Tech. Phys. Lett. 31 500-2; 2008 J. Appl. Phys. 103 033303

[51] Massines F, Gherardi N, Naudé N and Ségur P 2005 Plasma Phys. Control. Fusion 47 B577-88; Naudé N, Cambronne J-P, Gherardi N and Massines F 2005 Eur. Phys. J. Appl. Phys. 29 173-80; Brandenburg R, Maiorov V A, Golubovskii Yu B, Wagner H-E, Kozlov K V, Behnke J F, Behnke J 2005 J. Phys. D: Appl. Phys. 38 2187-98; Golubovskii, Yu B, Maiorov V A, Behnke J and Behnke J F 2002 J. Phys. D: Appl. Phys. 35 751-61; 2003 J. Phys. D: Appl. Phys. 36 30-49; Golubovskii, Yu B, Maiorov VA, Li P and Lindmayer M 2006 J. Phys. D: Appl. Phys. 39 1574-83; Luo H, Liang Z, Wang X, Guan Z and Wang L 2010 J. Phys. D: Appl. Phys. 43 155201

[52] Panousis E, Papageorgiou L, Spyrou N, Loiseau J-F, Held B and Clément F 2007 J. Phys. D: Appl. Phys. 40 4168-80

[53] Brandenburg R, Maiorov V A, Golubovskii Yu B, Wagner H-E, Kozlov K V, Behnke J F, Behnke J 2005 J. Phys. D: Appl. Phys. 38 2187-98

[54] Nikandrov D S and Tsendin L D 2005 Tech. Phys. 50 1282-94

[55] Kudryavtsev A A and Tsendin L D 2002 Tech. Phys. Lett. 28 1036-42; Golubovskii Yu B, Maiorov V A, Behnke J and Behnke J F 2003 J. Phys. D: Appl. Phys. 36 975-81; Naudé N and Massines F 2008 IEEE Trans. Plasma Sci. 36 1322-3

[56] Golubovskii Yu B, Maiorov V A, Behnke J F, Tepper J and Lindmayer M 2004 J. Phys. D: Appl. Phys. 37 1346-56

[57] Masuda S, Washizu M, Mizuno A and Akutsu K 1978 Boxer charger - a novel charging device for high resistivity powders in Proc. IEEE/IAS Annual Meeting (Toronto, Canada, 1-5 October 1978) vol 1B 16-22; Masuda S, Akutsu K, Kuroda M, Awatsu Y and Shibuya Y 1988 IEEE Trans. Ind. Appl. 24 223-31

[58] Allegraud K 2008 Décharge à barrière diélectrique de surface: physique et procédé Ph D Thesis (Palaiseau, France: Ecole Polytechnique) http://pastel.paristech.org/4783/

[59] Williamson J D, Trump D D, Belzinger P and Gianguly B N 2006 Comparison of high-voltage ac and pulsed operation of a surface dielectric barrier discharge J. Phys. D: Appl. Phys. 39 4400–6

[60] Allegraud K, Guitaletta O and Rousseau A 2007 J. Phys. D: Appl. Phys. 40 7698-706

[61] Lichtenberg G C 1777 Novi Comment. Goett. 8 168-90

[62] Gibalov V I and Pietsch G J 2000 The development of dielectric barrier discharges in gas gaps and on surfaces J. Phys. D: Appl. Phys. 33 2618-36; 2004 J. Phys. D: Appl. Phys. 37 2082-92

[63] Kozlov M V, Sokolova M V, Temnikov A G, Timakov V and Vereshchagin I P 2003 Plasmas Polym. 8 179-97

[64] Šimor M, Ráhel J, Vojtek P, Černak M and Brabcic A 2002 Appl. Phys. Lett. 81 2716-8; Černák M, Čermáková L, Hudec I, Kováčik D and Zahoranová A 2009 Eur. Phys. J. Appl. Phys. 47 22806

[65] Štefečka M, Korzec D, Širý M, Imahori Y and Kando M 2001 Sci. Technol. Adv. Mat. 12 587-93

[66] Kashiwagi Y and Itoh H 2006 J. Phys. D: Appl. Phys. 39 113-8; Allegraud K and Rousseau A 2009 IEEE Trans. Diel. Electr. Insul. 16 435-9

[67] Tanaka M, Murooka Y and Hidaka K 1987 J. Appl. Phys. 61 4471-8

[68] Gibalov V I, Tkachenko I S and Lunin V V 2008 Russ. J. Phys. Chem. A 82 1020-23; Solov’ev V R, Konchakov A M, Krivtsov V M and Aleksandrov N I 2008 Plasma Phys. Rep. 34 594-608

[69] Hoder T, Sira M, Kozlov K V and Wagner H-E 2008 Investigation of the coplanar barrier discharge in synthetic air at atmospheric pressure by cross-correlation spectroscopy J. Phys. D: Appl. Phys. 41 035212

[70] Srivastava A K and Prasad G 2008 Phys. Lett. A 372 6101-6

[71] Boeuf J P, Lagmich Y, Unfer T, Callegari T and Pitchford L C 2007 J. Phys. D: Appl. Phys. 40 652-62; Hoskinson A R and Hershkowitz N 2010 J. Phys. D: Appl. Phys. 43 065205